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SUNSPOTS IN ACTION

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2

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FOREWORD

It is a privilege, which I deeply appreciate, to be permitted to write a foreword to this book, written by my friend, Dr. Harlan T. Stetson. I regard it as a symbol of the warm and intimate collaboration which has long existed between the workers of our two countries in the particular field of science with which this volume deals.

As the reader will discover so readily for himself, the growth of our knowledge of the relationship between solar and terrestrial phenomena has resulted from the efforts of many people, in many countries; and, when the interchange of ideas and the association of effort between those people has been free and spontaneous, the pace of progress has been correspondingly increased. There are simple and fundamental reasons why collaborative effort is necessary in studying the influence of the sun's emanations on our own planet. First of all, the earth is round, and not flat. The result is that solar radiations do not impinge with equal effect on all regions of the earth's surface. The second reason is that the earth is constantly rotating; and, since interesting solar features may occur at any time, it is necessary to have observers at different terrestrial longitudes, in order that none of these interesting events may be missed. The third important fact is that the earth itself is a great magnet, and, because of this magnetic influence, electrified particles of solar origin are constrained to travel, not in straight lines, but along curved tracks. Sometimes the curvature of these tracks is so great that such charged particles impinge on the side of the earth's atmosphere which is further from the sun. In other words, we get solar effects at night. Moreover such effects

occur with unequal intensity at different terrestrial latitudes because of the earth's magnetic qualities.

The sun's rays, in the form of light and heat, are found to be remarkably constant to the general observer, at ground level, though there are slight variations which can be measured with delicate instruments. But if we could take those instruments up beyond the top of the earth's atmosphere, as we soon may be doing by means of rockets, we should find that there are much more marked variations from day to day, and from year to year, especially in the strength of the ultraviolet rays in the sun's spectrum. The reason we do not observe such variations at ground level is that the greater part of the sun's ultraviolet light is absorbed in the higher reaches of the atmosphere. This absorption of energy is responsible for the liberation of electrons in the ionosphere. Every day, therefore, we can regard the sun as conducting an experiment in the Laboratory of the upper atmosphere. Its ultraviolet rays release electrons, so that they become free and thus play their part in causing the downward reflection of our radio waves. The result is that such radio waves travel usefully to long distances, and do not disappear wastefully into outer space. During the night the electron population decreases, but, fortunately for us, does not entirely disappear, so that radio wave reflection still persists. When morning comes the sun resumes its experiment, and the electron population builds up to its day-time level.

It thus comes about that the electron population at high atmospheric levels, when measured, say, at noon, is a very sensitive index of solar ultraviolet ray intensity. Now a most remarkable thing has been discovered about this electron population at great heights. Its density, which is of the order of a million free electrons in a thimbleful of air, has been found to wax and wane with the well-known cycle of sunspots. Such a variation of ionospheric electron density is of great practical importance in radio transmission, for it means that, during

years of maximum sunspot activity, the range of radio frequencies reflected by the ionosphere, and thus available for long-distance communication, is very much greater than during years of minimum sunspot activity. It is therefore most probable that, if you are interested in long-distance short-wave reception, you will, during the coming years of sunspot maximum, be receiving programmes at periods which would have been quite unworkable some few years ago when sunspot activity was at a minimum.

Unfortunately, however, this benevolent sunspot-cycle control of events in the ionosphere is not entirely unattended with unfavourable features. For it is found that, when sunspots are large and frequent on the sun's disc, two types of long-distance radio fade-outs are specially liable to occur. One of these types of ionospheric irregularities is associated with auroral displays and magnetic storms. As such untoward effects exhibit a 27-day recurrence tendency, since they are usually associated with a particular aspect of a large sunspot group on the sun's disc, it will be seen that, in the radio planning of an important world-wide broadcast, it is possible so to date it as to avoid a period likely to be troublesome.

I have mentioned the particular example of the effect of sunspot activity on the ionosphere because it illustrates one of the most striking ways in which sunspots influence the lives of human beings, here on the earth. But this relation, and many others, are dealt with at length by Dr. Stetson.

Since the results of scientific research are the possessions of mankind as a whole, I am strongly of opinion that it is the scientist's mission not only to uncover nature but also to interpret his results to his fellow men. Scientific knowledge is itself neutral. It is the use that is made of it that is good or evil. Decisions concerning that use are not for the scientist alone. The layman must therefore make his own efforts at understanding. To assist him, the scientist must, in turn, be ready to leave

his laboratory and act as a guide. I regard this volume as one striking example of such volunteer effort. In it the fascinating field of sunspot activity and its terrestrial consequences is explored and expounded by Dr. Stetson, who is himself a pioneer in this territory. Indeed, the reader could not have a more learned or a more friendly guide.

EDWARD V. APPLETON

London, England
July 2, 1947

PREFACE

SUNSPOTS and accompanying solar radiations have become so important a factor in radio communication that an up-to-date summary of the effect of sunspots upon the earth and its atmosphere from this viewpoint appears in order. A decade has passed since the publication of *Sunspots and Their Effects,* and more than a decade since the appearance of *Earth, Radio, and the Stars.* We are now approaching another sunspot maximum. So much has happened in the last ten years with the rapid progress of science that a new book on the subject appears preferable to any revision of an earlier volume.

The aim of this book is to bring together relevant information crossing several fields of science that bear upon the relation of the earth to its cosmic environment. The book has been written for the intelligent layman who would keep informed with the advance of science, and particularly for those interested in the fundamental relations of the sun to the earth. Considerable emphasis has been placed upon the effect of the sun on the earth's atmosphere both as a medium for long-distance radio communication and as the ultimate source of weather.

Many recent books cover the fields of electronics and radio communications, but for the most part such volumes as have appeared devote scarcely more than a chapter to the propagation of radio waves through the atmosphere, with a casual mention of such relations as have been found to exist between sunspots and the electrical ionization of the upper air.

Since the book has been written primarily for the layman, technical language has been reduced to a mimimum with the hope of thereby presenting a clearer and broader picture, even

at the sacrifice of certain details which might be appropriate in a more technical volume.

Sunspots made their contribution to the war effort by frequently giving forewarning, days in advance, of anticipated blackout periods in radio communication. On many occasions communication predictions based on sunspots were of inestimable value to the military authorities, who had of necessity to keep communication channels open both to the European and to the Pacific theaters of operation in the combat zones.

In peacetime radio, the future success of long-distance communication, the performance of entertainment radio beyond the primary ground-wave range, and the satisfaction to be gained from the new frequency allocations for Frequency Modulation and television may rest in no small measure upon the guidance furnished by a study of the sun and the sunspot cycle.

So much interest persists in the fields of speculation regarding sunspots, particularly as to their possible correlation with economic trends, that a chapter has been included on "Sunspots and the Economic Cycle." Much of the material of this chapter appeared in *Dun's Review* for October, 1946, under the title "Sunspots and Business Activity."

Acknowledgment is due Dun and Bradstreet for permission to reproduce the old chart used in Figure 39. To Mr. James Stokley and the General Electric Company I am indebted for the use of a diagram illustrating frequency modulation. The recent photograph of the McMath-Hulbert Observatory of the University of Michigan, and the excellent spectroheliogram of the sunspot group of July 28, 1941, were kindly furnished through the courtesy of the Director, Dr. Robert R. McMath. The United States Naval Observatory gave permission to reproduce the large sunspot of February 8, 1946, used as Plate I. Permission was granted by Caldwell-Clements, Inc., to reproduce the Cross Section of the Earth's Atmosphere, originally

prepared under the direction of the author for a colored plate in *Electronic Industries*.

Acknowledgment is due the McGraw-Hill Book Company for freedom to draw on certain material in my earlier books and to many other colleagues for other material to which reference is made. Especially to be mentioned are the Central Radio Propagation Laboratory of the National Bureau of Standards, and the Department of Terrestrial Magnetism of the Carnegie Institution of Washington.

For the benefit of the many who continue to inquire for sunspot numbers, a table in the appendix gives the mean monthly Wolf and Wolfer sunspot numbers as published at Zurich from the year of reliable counts, 1749, to the year 1947.

A bibliography is appended for those who would pursue the subject further, listing, chapter by chapter, references to original sources.

HARLAN T. STETSON

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July, 1947

CONTENTS

Appendix

ILLUSTRATIONS

PLATES

SUNSPOTS IN ACTION

Chapter 1

ATOMIC ENERGY AND THE SUN

On an eventful Monday morning, July 16, 1945, the first experimental atomic bomb was secretly set off at Alamogordo, New Mexico. There was for one brief moment a blaze of light such as never before had been seen by man. It outshone the sun in brilliancy. Three weeks later, on August sixth, an atomic bomb was dropped with devastating effects on Hiroshima. The World then knew for the first time that man had mastered a new secret of nature, the release of energy from within the nucleus of the atom. Thus was precipitously ushered in a new era of atomic energy with possibilities that stagger the imagination. Never before has so startling a discovery in science been announced with such violence. However, this was not introducing a new kind of energy into the universe. To the uninitiated it may be something of a surprise to be told that atomic energy is nothing new. For billions of years atoms have been splitting with the release of just such energy wherever stars are shining. We know now that atomic energy is being released from the sun and stars, and that this process has been going on for unthinkable years. It is the transmutation of atoms within the interior of the sun that has been the source of light and heat that has made all life on the earth possible.

Unlike the sudden release of the chain reaction that takes place when an atomic bomb explodes, the sun's atomic energy is under such control within the solar laboratories that the amount of radiation released from the sun has been remarkably constant for millions of years. Solar physics has been at work

ages before man learned how to split the atom or could conceive of the idea of any "Manhattan" project for national defense. As we shall see later, it was a physicist by the name of Hans Bethe, who, in 1939, first worked out the atomic physics and gave a true explanation of the source of solar energy. It is perhaps a bit unfortunate that for years to come, whenever we think of atomic energy, we shall think of the atomic bomb and its devastating effects. However long it may take for man to learn the secret of so slowing down the chain reactions of the atomic bomb as to harness atomic energy for useful purposes, no one yet dares predict. Yet it is a consoling thought to know that the sun has long since learned the secret of releasing this dynamic force with such perfect control that the earth receives an almost constant supply of light and heat in an amount best suited for the well-being of mankind.

There are times, however, when apparently accidents can happen even in the solar laboratories; for explosions do occur on the sun that cause effects on the earth out in a safety zone of space 93 million miles away from the sun. On such occasions we can say that in a fairly true sense an atomic bomb has exploded on the sun. These solar explosions occur most frequently when the sun shows on its otherwise uniformly bright surface dark blotches familiarly known as sunspots. Long before astronomers found out that sunspots were centers of terrific atmospheric disturbances on the sun, they had been observed to come and go with a certain amount of regularity. An unusually large sunspot can sometimes be seen with the naked eye when the sun is setting; for then the glare of its light is greatly reduced by absorption in the low-lying layers of the atmosphere. Such occurrences of sunspots must have been regarded as of considerable importance by the ancients, for we find many notations of such in the annals of the early Chinese dynasties. By the middle of the eighteenth century, after the invention of the telescope, sunspots came to be observed regularly, and we have reliable

counts of their numbers as they occurred from about 1750 to the present time.

Today, sunspots make front-page news when they cause such serious disturbances in the earth's atmosphere as to black out radio communication, sometimes for hours and days. Electrified particles shot earthwards, and photons traveling with the speed of light from these disturbed regions on the sun, so electrify the upper reaches of the earth's atmosphere as to impede the path of the magic waves of radio. Large sunspots precipitate electric discharges hundreds of miles high giving rise to auroras, or the northern lights, that often blaze with great brilliancy like neon signs in high heaven, advertising a big show on solar Broadway. Rivers of electrons start flowing aloft in the invisible air inducing electric currents in the earth that even interfere with telegraph lines and teletypes, garbling messages with the caprices of a thousand gremlins.

To know more about sunspots, what causes them, what their far-reaching effects on the earth may be, and how to predict or foretell the occurrences of these violent eruptions on the sun is one of the pressing problems of science today. It is a problem of immediate concern to broadcasting companies and communication engineers. To appreciate something of the gigantic size of solar disturbances, we may well be concerned for the moment with the sun itself, the most important of all astronomical bodies for the inhabitants of the planet earth.

While to us the sun has no rival as the brightest and most conspicuous object in the sky, it is in reality quite an ordinary star. If the earth were as far away from the sun as it is from the stars of the "Great Dipper," the sun would be totally invisible to the naked eye. At such a distance, the brightest star in the Dipper would be outshining the sun some 14 thousand times. In comparison with the earth in size, however, it is well to remember that the diameter of the sun is 109 times that of the earth or approximately 865,000 miles. Curiously enough, the

moon and the sun appear to be of about the same size as they are seen in the sky, due to the fact that the moon is so much nearer to the earth. Compared volume for volume, in round numbers the sun is a million times larger than the earth, yet there is a bright red star in the constellation of Orion, named Betelgeuse, which is more than a million times as big as the sun. The sun is the central body of the solar system about which the planets revolve, yet if the sun were placed in the center of the star Betelgeuse, the orbits of the planets Mercury, Venus, Earth, and Mars would all be contained within that giant star.

The average distance of the earth from the sun is very nearly 93,004,000 miles, a distance that could now be covered by rocket ship, traveling 1,000 miles an hour, in about ten years. News flashes sent from the sun on the wings of light consume eight minutes in revealing to us happenings on the sun, even though light waves travel at the incredible speed of 186,000 miles a second. A news flash from the next nearest star would be four years old before we read the headline in our newspapers. While, as astronomical distances go, the sun is a very neighborly star, it is a member of what we call the galactic system comprising some 30 billion stars that make up the Milky Way. Were a message from the solar system to be sent to the outskirts of the remotest galaxy for rebroadcasting back to us, we should have to wait a hundred million years for returned news. A message received today would be telling us what the earth was like a hundred million years ago.

Everyone is aware of two rather obvious motions of the sun, its daily path across the sky and its yearly movement which carries it north in the summer and south in the winter, motions which are in reality due to movements of the earth and not of the sun at all. The sun does, however, have two motions of its own; it rotates on an axis as does the earth, but instead of turning around once in 24 hours, it takes about a month for one rotation. Moreover, the length of the "day" on the sun is not

constant. The sun rotates much more slowly at points far north and far south than it does in lower latitudes. While points near the equator complete a rotation in 25 days, those as far north as 60 degrees from the sun's equator move so slowly that 35 days are necessary to complete one rotation. This of course could not be the case were it not for the fact that the sun is gaseous by nature. The unequal rate of rotation of the gaseous surface of the sun probably is a very important factor in causing the disturbances in its atmosphere that give rise to sunspots.

Besides rotating on its axis, the sun is also moving through space among neighboring stars at a speed of twelve miles a second, or 40,000 miles an hour. We on the earth, along with the other planets, are participating in one of the grandest joy rides in space. If at this moment you should stop reading and replace this book on the shelf from which you have taken it, say ten minutes ago, you will really not be putting it back in the same place at all, for its familiar location will be 6,500 miles away from where it was in space when you picked up the volume. Fortunately, our surroundings have likewise moved and, to all practical purposes, the book appears to us to have been returned to its familiar place of hiding. At the beginning of each new year the earth is 400 million miles further on in space from where it was when the previous year started. In spite of all our journeyings, our distance from the sun varies only slightly while the earth swings about it in a perceptibly elliptical orbit. Were our distance from the sun to change materially, we should soon be frozen, on the one hand, or overcome by the terrific heat on the other.

Because of our proximity to this nearest of all stars, we are able to learn much about what the surface of a star looks like. The brilliant round disk of the sun which emits light and heat, and which in the telescope appears to have a finely mottled structure, is known to the astronomers as the "photosphere," literally the light-sphere. Overlying the brilliant surface of the photo-

sphere there is a shell composed chiefly of hydrogen gas and calcium vapor. While not ordinarily visible except during total eclipses of the sun, it is brilliant red in color and for this reason has been called the "chromosphere" or color-sphere. It is from this chromosphere that astronomers frequently observe huge bursts of hydrogen gas, sometimes obtaining heights of 100,000 miles or more within a very few minutes as though an atomic bomb had exploded. Stretching way out beyond the chromosphere is the corona giving a peculiar mysterious light that crowns the sun during a total eclipse. The light of the corona is variable, as every eclipse observer knows, and in recent years it has become possible to photograph the coronal light with suitable instruments without waiting for total eclipses of the sun. As the corona changes its shape and light with the appearance and disappearance of sunspots, more attention is being paid to the radiation of this outlying solar appendage as a possible index of what may be happening on the sun itself.

The temperature of the sun's surface can be measured with devices similar to optical pyrometers used in measuring the temperature of blast furnaces. From such measurements scientists have deduced that the surface of the sun (the photosphere) has a temperature of about 12,000 degrees Fahrenheit. From theoretical considerations it has been deduced that temperatures within the interior of the sun rapidly rise to many millions of degrees and perhaps at the very center a hypothetical thermometer would register as high as 40 million degrees Fahrenheit.

Chemically considered, the sun is composed of much the same sort of materials as exist in the earth. Some of the elements with which we are quite familiar appear to be much more abundant on the sun than they are in the earth's crust. Among the more familiar elements, hydrogen, calcium, sodium, magnesium, and iron appear to be most conspicuous in the sun's make-up. There are now known to be ninety-six different chemical elements that have been discovered on the earth.

Some of these have not yet been revealed as existing in the sun. It appears probable, however, that in one form or another, the same building blocks which constitute the earth will be found to exist in the sun. Pressures and temperatures are so high within the solar interior that the physical state of the various elements must be vastly different from that in the earth. Atoms, which we now know consist of protons, neutrons, and surrounding electrons, would probably be unrecognizable to any physicist as they exist in the sun's interior. In the vernacular of the physicist, they are "stripped atoms," a phrase meaning that all of the outer electrons have been torn away from the nucleus.

When we look at the sun through the telescope, we must use adequate protection for our eyes. Dark glasses, which may be sufficient for a naked-eye view of the sun, can be easily cracked by the sun's heat pouring through the lens of a telescope, and many an eye has been injured by such an unfortunate accident. The astronomer uses various devices for diluting the sunlight coming through the telescope, devices which, unlike dark glasses, do not change the natural color of the sunlight. However, such elaborate accessories to the telescope are not necessary. A white card held a few inches away from the eye end of even a small spyglass, directed toward the sun, will receive a picture of the solar image showing whatever spots may be in evidence on the photosphere at the time the observer is viewing the sun's surface. With more elaborate equipment, photographs of the sun are being made daily by observatories scattered over the world in order that not a day may be lost in following the panorama of events on the sun's surface. Sunspots have been observed systematically for nearly two hundred years.

It was an odd genius, a professor at the University of Padua by the name of Galileo, who as far as we know first turned the telescope to the sun and found it besmirched with spots that drifted slowly day after day across its surface. This showed to Galileo that the sun rotated on its axis, as does the earth, carry-

ing these curious markings across its surface at such a rate as to indicate that the sun turned completely around once in about twenty-eight days. Had Galileo contrived his telescope a few years earlier or a few years later, he might have found the sun a rather uninteresting object lacking in all details worthy of observation; for sunspots are not always present on the sun and have a way of appearing and disappearing in a most uncanny fashion. Some years, days, or weeks may pass without the occurrence of a single sunspot. In other years, on almost every day, the sun is pockmarked with these little black areas. The early astronomers must have noted that the intervals between times when sunspot traffic was at a maximum stretched over a period of about ten years.

However, credit for the discovery of the sunspot cycle seems to be rightfully attributed to a man by the name of Samuel Heinrich Schwabe. With the intellectual curiosity characteristic of a true scientist, Schwabe began his work on the sun in the early part of the nineteenth century, painstakingly counting the spots that appeared day after day and year after year. After nearly twenty years of observations, he published his findings in 1843 and showed that the interval between the periods of greatest sunspottedness was something of about a decade's duration. From the accumulated records of the last two hundred years, it has been shown that on the average 11.2 years elapse between successive sunspot maxima. This period, however, is not a definite one. Sunspots are quite a bit irregular in their habits. Sometimes not more than nine years have elapsed between rush hours in sunspot traffic, and sometimes as long as seventeen years have elapsed between periods of greatest spottedness.

While these spots on the sun appear very small to the observer, as compared to the size of the solar disk, they are in reality no pygmies. It must be remembered that the sun itself is a hot ball of glowing gas a million times the size of the earth in volume. It is an easy trick for astronomers to measure the

diameter of the sun, which is known to be 865,400 miles across, about 109 times the diameter of the earth. If we measure the size of a sunspot in comparison with the visible solar surface, we find that the most ordinary spot is big enough to contain the entire earth. On occasion an unusually large spot, or group of spots, may stretch over the sun's surface for a hundred thousand miles or more, actually involving billions of square miles in area. While these spots appear dark as seen in the telescope, they are in reality intensely brilliant and appear dark only by contrast to the much greater brilliance of the sun itself. They will often break out as small insignificant dots enlarging day by day with accompanying secondary disturbances. They may persist for days or weeks before they ultimately disappear; or they may be lost from view as the rotation of the sun, turning on its axis, carries them around to the far side of the sun. Not infrequently a conspicuous spot may reappear at the edge of the sun after completing a full rotation or more. The longest enduring spot on record occurred in the years 1840 and 1841. It was thought to be identified as the same disturbance for eighteen months before it disappeared.

We are now, in 1947, well near the top of a new sunspot period which began early in 1944. The largest spot of the present cycle appeared in February, 1946, a spot then reported as the largest sunspot on record for twenty years. We may anticipate increasing numbers of sunspots and even more violent solar disturbances during the next few years.

An interesting characteristic of the sunspot cycle is that the first spots of a new series begin to break out in high latitudes on the sun about halfway between the sun's equator and the pole. They may occur either in the northern or in the southern hemisphere of the sun. As the sunspot cycle progresses, new groups will appear at lower solar latitudes until by the end of the series, fresh outbreaks diminishing in number and in size will occur within a few degrees of the solar equator. The effect of sunspots

on terrestrial disturbances appears to be more marked in the latter half of the sunspot cycle. It is then, by reason of the sun's rotation and position, that they more often pass in the direct line from the sun to the earth.

There have been many speculations as to the possible effect of the sunspot cycle on the earth and on human events. Those who have a flare for studying cycles and are statistically minded have attempted to show certain correspondences between epidemics, migrations of wildlife, agricultural and economic cycles with the sunspot period. Even Florida hurricanes have been blamed on sunspots. However, one of the most persistent ideas is that sunspots influence weather. In general, meteorologists already overwhelmed with the complexities of hydrodynamics of the atmosphere have shown little enthusiasm for injecting into forecasting the additional oddities of sunspot behaviour. Many serious attempts, however, have been made, as we shall see later, to connect solar disturbances with the passing of storms across the United States and other countries. There are some good reasons for believing that solar disturbances accompanying the sunspot period may very considerably affect the earth's atmosphere. However, the connecting link is not a simple one. The problem of untangling such relationships is complex, but it may be one of the most important problems for science yet to solve.

Whatever the vagaries of the weather, and however skeptical one may be as to the effects of sunspots on meteorology, even the most conservative scientist recognizes that after all the sun is the prime weather breeder. It is the heat of the sun warming the earth's atmosphere that is the cause of its convection currents that are fundamentally the basis for all our weather changes. It has been truly stated that without the sun we should have no weather on the earth to predict or to talk about.

There are so many businesses that are affected directly or indirectly by weather that one cannot estimate the economic

value of any discovery that would be helpful in predicting open or severe winters, hot dry summers, or cold, wet ones. We know from the studies of climatology that there have been intervals of abnormal rainfall interspersed with years of drought. How many of these abnormal years could have been predicted had we had fuller knowledge of the sun and its relation to weather-making we do not at the moment venture to say.

While the light and heat received by the earth from the sun are surprisingly constant, we do know that there are small variations from day to day and from week to week in the amount of energy released from the sun. Some of these changes have appeared to follow the outbreaks of sunspots. If we ever come to the time when we can make reliable long-range weather forecasts, recognition of the various changes on the sun may prove to be a dominant factor in such prognostications.

Irrespective of what relations may exist between the sun, sunspots, and the weather, we do know that changes on the sun, following the cycle of the sunspots, produce profound effects in the electrical state of the earth's upper atmosphere. Most of our knowledge concerning this comes with the advent of radio. Of these subjects more will be said later. Meanwhile we shall consider the enormous amount of energy pouring from the sun, and in the light of recent discoveries of science examine the source from which the solar energy emanates, and the kinds of atomic radiation which are to be found coming from the sun.

Chapter 2

THE SOLAR POWERHOUSE

HAVE YOU EVER thought of the many different ways in which the earth utilizes solar energy? In addition to the light and heat which make all vegetation on the earth possible, the sun is also responsible for all of our rainfall. Reliable figures give the average rainfall for the whole earth as 32 inches per annum. If this amount should fall all at one time, it would flood the entire globe with a sheet of water nearly three feet deep. The weight of this amount of water is 480 million million tons.

All of this must have been evaporated from the lakes, rivers, and oceans and lifted to a cloud height of some 4,000 feet before it dropped to earth again as rain. To carry on this gigantic irrigation enterprise requires the expenditure of 220 billion horsepower continuously throughout the year. So far as we know, this irrigation system has been at work for thousands and millions of years, yet only a very small amount of the total solar energy falling on the earth is consumed in running this rain-making machine.

Have you ever stopped to consider what it would cost to light the world with sunshine if we had to pay for it? It has long been known that every square yard of the earth's surface directly exposed to the sun's rays receives on the average one and one half horsepower. We pay our electric light bills in terms of kilowatt hours. If we think of the supply of sunshine as a public utility, we might say that every square yard on which the sun shines is receiving from the Solar Power Company one and one eighth kilowatts continuously.

The price of electric current varies somewhat from place to place depending upon the distance from the source of fuel supply, the cost of labor, taxes, and other items. The rates for electric current are usually established on a sliding scale, the cost decreasing proportionately as greater amounts of electricity are consumed. Initially, I pay six and one half cents per kilowatt hour for the first twenty kilowatts used. If, however, I would emulate the painter who paints fast before his paint gives out, and turn on a good many lights, heaters, and flatirons, I would soon use up the first twenty kilowatts of electricity and toward the end of the month may be paying as low as three cents per kilowatt hour. Where large amounts of power are consumed, we may make a fair assumption for the price of current as one and one half cents per kilowatt hour. At this rate, the cost of sunshine for just one twelve-hour day for the city of greater New York would amount to two hundred million dollars. The cost for one twelve-hour day of sunshine for the whole earth would be more than one hundred million times a million dollars. If our Federal Government were to have to pay for sunlight for the continental United States alone, it would call for an annual budget of 686 trillion dollars. This is a figure which reduces to relative insignificance even the two hundred billion dollar deficit that World War II thrust upon us. Fortunately, nature provides the sun's light and heat gratis. No Congressman has yet attached a rider to any revenue bill calling for a tax on sunshine and, I venture, is not likely to do so.

Such examples give us an idea of the enormous amount of energy coming from the sun and received by the earth. Yet we must remember that the sun is radiating energy in all directions into space. The distance from the sun to the earth is so great, and the earth so small in comparison, that it actually intercepts only one two-billionth of the total amount of energy emitted from the sun into space. Expressing it another way, we might say that for every kilowatt the earth receives, two billion kilo-

watts are lost in interplanetary space. The total amount of energy received by the earth, therefore, must be multiplied two billion times to arrive at the total output from the Solar Powerhouse. This gives the sun a total capacity of 343,000,000,000,000,000,000,000 kilowatts. Evidently the solar dynamos are running full tilt, and yet they maintain continuous and constant service.

What is the fuel supply that keeps this power plant in operation? This has been one of the questions that has long puzzled scientists, and it is only recently, with the advent of the atomic age, that we have sensed the real source of supply. We on the earth are so dependent upon the light and heat of the sun which has already been supplied for millions of years that we may well desire to know how long the Solar Power Company may remain solvent, and whether any shutdown is imminent while human beings inhabit the planet Earth. Someday the sun undoubtedly will give out, but we are quite powerless to conserve any of its enormous waste for any future needs.

Millions of years ago sunshine provided the energy for growing the vast tropical forests of the carboniferous era. It is the carbon in those fallen tree trunks that we are mining today in the form of coal, the chief source of fuel for our own public utilities. Thus nature has stored in those primitive forests buried underground unthinkable calories of canned sunshine that turns the wheels of industry and illuminates our buildings during the long nights when the sun is below the horizon. It is likewise this sunshine of the past that heats our homes, factories, and offices during the period of the year when in northern climates life would be unthinkable without artificial heat. Even our health lamps glow with ultraviolet light by reason of past sunshine, sunshine which made possible the Pennsylvania forests of those days when dinosaurs innocently roamed without a thought that they would be decorating the billboards of our national highways proclaiming the merits of Sinclair oil.

If we live where we obtain our electric current from hydroelectric companies, we do not dodge the issue of our debt to the sun. We have seen that the sun transforms the water of the lakes and rivers into ascending water vapor that condenses into clouds and falls to earth again as rain, feeding mountain streams and rushing torrents that turn the giant turbines of the power plants of Niagara, Boulder Dam, and the Tennessee Valley Authority.

There have been many hypotheses to account for the maintenance of the sun's radiation. It is quite easy to think of the sun as a burning furnace where combustion is taking place. This, however, is a very erroneous explanation of the sun's source of heat. Strange as it may seem, the sun is too hot to burn. Burning is an oxidation process. The temperature of the sun, with the exception of the interior of sunspots, is far too hot to allow oxygen to combine with any other element in any true chemical sense. In the sunspots, where the temperature is somewhat lower than on the rest of the surface, there is indication that oxygen does combine with some of the other elements, forming the oxides which are visible as dark absorption bands in the spectroscope. But were combustion taking place in the sun, and were we to suppose that the sun was composed of the hardest anthracite coal burning under ideal conditions, calculations show that the sun could not have kept up anything like its present rate of radiation for more than 1,500 years. Life could not have started on any planet with so short a span of light and heat.

It is for this reason that scientists a century ago began to consider other explanations for the maintenance of the sun's heat. In any man-operated powerplant, the source of fuel invariably comes from the outside. Perhaps it was for this reason that scientists once held that matter must be coming into the sun from the outside to keep up its present output. With this in mind, they postulated that meteors falling into the sun

were the chief source of its heat and light supply. Fortunately, however, this idea could be checked against experience. Meteors are constantly falling on the earth. A reliable estimate places the number of meteors received by the earth in a year as probably many millions. From this estimate of the amount that this little earth encounters, we can judge the meteoric matter in space, and so calculate the amount of meteoric matter that could reach the sun. This was found to be totally inadequate as a source of fuel supply for the sun's heat. On the most optimistic estimates, it does not appear that the sun could have kept up its present rate of radiation on this basis for more than ten thousand years at a maximum. Scientists therefore came to the conclusion that the sun's source of energy must lie within itself.

Scientists know that the sun is largely gaseous and the material of which it is composed must be subject to gravitational attraction which would tend to draw this material closer to the sun's center thereby increasing constantly the pressure toward the interior. It was the scientist Helmholtz, who, in 1854, seriously applied this idea to calculating the amount of energy that could be generated because of the fact that the sun constantly tended to shrink in size. In this shrinking hypothesis, Helmholtz concluded that were the sun to shrink but two hundred feet a year it could account for its present rate of output. However, this did not prove to be the final answer, for it was soon found that at this rate of shrinking the sun could have been radiating at this rate for scarcely more than ten million years.

From geological considerations, such as the rate of deposit of salt and the rate of formation of sedimentary rock in the earth, even the geologists of the nineteenth century realized that the earth must have been receiving something like the present amount of solar radiation for at least one hundred million years. Since the discovery of radioactivity, it has been possible to arrive at the earth's age more exactly from the rate of disintegration of radioactive materials in the earth. Present information places

the age of the earth at some two billions of years. Thus, the contraction theory of Helmholtz has long since "gone with the wind," along with the meteoric hypothesis. Neither theory has contributed adequately to the picture of what has kept the solar boilers going.

It is only within the last ten years while we have been making rapid strides in our knowledge of the atom that we have been able to arrive at any satisfactory solution of the supply of solar energy.

It is common knowledge today that all of the various chemical elements are composed of electrons, protons, and neutrons. These are the fundamental building blocks from which all substances are made. Whether we consider the materials in the earth, in the sun, in the remotest star, or in the human body, all substances and the varied properties which they exhibit depend upon the arrangement of these fundamental building blocks of nature. Ordinary water is a compound of hydrogen and oxygen. Hydrogen is the simplest of all the atoms. A single atom of hydrogen consists of a positive charged nucleus and a tiny particle of negative electricity, which is called the electron, circulating about it in an orbit much as a planet circulates about the sun. The bulk of the matter in the hydrogen atom is contained in the nucleus which is nearly two thousand times as heavy as the little electron that revolves about it. An atom of helium has the next simplest structure to hydrogen. It weighs a little less than four hydrogen atoms, and the nucleus has four planetary electrons revolving about it.

For a long time we have surmised that through some secret process of nature hydrogen atoms might combine to make one helium atom with about 1 per cent loss of weight in the combination. This loss in weight, due to whatever transformation takes place, represents an equivalent amount of energy which can be radiated into space as light and heat. The process, however, is not a simple one. It was Professor Hans Bethe, to whom refer-

ence was made in the first chapter, who first worked out a detailed process by which hydrogen might be transformed into helium within the sun, resulting in a tremendous output of solar energy. Professor Bethe, working at Cornell University, has shown that much help is needed on the part of carbon to make this transformation take place. The sun is rich in carbon as well as in hydrogen. The story of this complex process is much as follows: When one of the carbon atoms in the sun hits the nucleus of the hydrogen atom (in reality a proton) the proton is absorbed in the encounter and in place of the carbon there results a special form of nitrogen lighter in weight than ordinary nitrogen. This form of nitrogen is known to be radioactive and disintegrates readily into another form of carbon, a little heavier than the ordinary carbon with which we started. In the excitement of activity within the hot sun, this carbon atom is soon struck by another proton which will produce another change into ordinary nitrogen. Shortly, another hydrogen nucleus will encounter this atom, producing another form of oxygen which is radioactive and that will later turn into a stable form of nitrogen. When this stable form of nitrogen is bombarded by another proton, it splits up into two kinds of atoms, one of which becomes helium. At the end of this cycle in the manufacturing process, hydrogen has been made into helium and we have the kind of carbon with which we started. The oxygen and nitrogen were merely incidental in the process, although they formed a very important part in the manufacturing. Physicists can calculate that for every 400 grams of hydrogen changed into helium in this way, about three grams of matter disappear as radiant energy, the heat and light of the sun. Knowing the total amount of matter in the sun, it can be calculated that the energy released in this fashion is quite sufficient to maintain the sun's temperature at its present value for some thirty-five billions of years. Of course the sun is losing weight in the process. This loss of weight going over into energy represents

four million tons of matter that have disappeared every second. We scarcely need worry about the sun itself disappearing with its fuel supply diminishing at this rate, for the sun, still, has 2,000,000,000,000,000,000,000,000,000 tons of matter left in it! Ultimately, however, the sun must gradually lose temperature and become a cold and dark star. Of course, other things might happen in the meantime. Should another star collide with the sun, or should the sun suddenly explode on account of some atomic instability, the earth would unquestionably be burned to a crisp. When we frequently observe a nova or so-called "new star" suddenly blaze forth in the heavens, we realize that such a catastrophe does occasionally take place in the universe. It is at least consoling to know that modern physics gives us a picture as to where the heat of the sun comes from. The probability that it will outlast the human race may be a fair assumption.

Many various attempts have been made to utilize the large amount of solar energy falling on the earth by converting it into mechanical power. Years ago huge reflectors which concentrated the sun's rays on a steam boiler were set up in Southern California. A steam engine was actually put into operation by the sun's heat and pumped water for irrigation purposes. Economically, however, this contrivance entailed an expensive upkeep and was soon abandoned. Various other attempts have been made, notably by Dr. C. G. Abbot of the Smithsonian Institution, to build solar engines utilizing the principle of the flash boiler that would more efficiently transform the sun's heat into mechanical work. A few years ago a Boston businessman, Mr. Godfrey Cabot, gave $600,000 to the Massachusetts Institute of Technology as a Solar Energy Research Fund to aid in the investigation of more effective methods of converting sunshine into mechanical energy. When, ultimately, the limited sources of coal and oil are near exhaustion, solar energy may provide another possible source of power for industrial activities. It now appears, however, that solar energy will find a strong

competitor in the atomic age. Now since man has learned, through the invention of the atomic bomb, to understand the secret of unlocking the tremendous storehouses of energy within the atom itself, it seems likely that atomic energy may be developed more cheaply than we can harness the energy from the sun falling on the waste parts of the earth. Many years may elapse before we have atomic energy so controlled as to compete with coal and oil at present prices. It has been calculated that when Uranium 235, or some other substance from which atomic energy can be readily released, can be manufactured at a cost of $1,340 per pound we shall indeed have a new source of fuel that can compete with mining coal or the refining of petroleum.

Quite apart from the heat and ordinary light which come to the earth from the sun, the sun renders a very subtle service to the well-being of mankind by sending us an invisible kind of radiation familiarly known as ultraviolet light. To measure all kinds of radiation coming from the sun, and the variations in these radiations which reach the surface of the earth, is one of the most important problems of science. What these kinds of radiation are and how they are measured we shall describe in the next chapter.

Chapter 3

METERING SUNLIGHT

If you have ever been an enthusiastic sun bather you have noticed that a protective tan is much more quickly developed in the summer than in the winter season. This is due to the fact that in summer, when the sun is high overhead, the ultraviolet rays that produce the tanning effect on the skin penetrate much more effectively through the earth's atmosphere than during the winter, when, on account of the low slanting rays of sunlight, the radiation must pass through a much thicker portion of the earth's atmosphere. The atmosphere absorbs most of the ultraviolet light which produces the tanning effect. Perhaps during the winter season you have tried ultraviolet light treatments under properly constructed health lamps. If so, you have probably noticed how, under adequate supervision, the time of exposure, or, as one might say, the "dose," is carefully measured. Carelessness in this regard can painfully remind one of the dangers of too much ultraviolet light.

A new instrument has recently been developed for measuring the proper doses of these health-giving rays. Quite appropriately it is called a "dosimeter," for its purpose is to measure the proper dose so that the exposure may be suited to the individual. The dosimeter is now in quite general use in clinics that specialize in ultraviolet treatment. One of these instruments has recently been in use at the Blue Hill Observatory in Milton, Massachusetts, for measuring the variation of ultraviolet light from the sun. Not only are the ultraviolet rays from the sun more intense in summer than in winter, but it appears that they are much more intense some summers than others. Some evi-

dence exists that the ultraviolet radiation from the sun varies with the sunspot cycle.

It is obvious that if we are going to make systematic studies of the intensity of sunlight, we need to know more about the real nature of the radiation which comes from the sun. Physicists are still debating technical theories of light. In a certain sense we have as yet no complete and wholly satisfactory simple picture of radiation that explains the exact mechanism by which the light and heat of the sun come to the earth. We shall not be very far wrong, however, if we picture the sun's rays as a series of waves or vibrations set up by the sun, which travel unhindered through space until they reach the earth. When they do reach the earth, some of these radiations are absorbed by the earth's atmosphere, others penetrate to the earth's surface where they warm the soil and are transformed into vegetation making life possible.

One may regard the sun as in a sense a big and powerful broadcasting station. The waves or pulses of radiation which the sun sends out do not differ very much in kind from the electric waves sent out from broadcasting stations. The chief difference lies in the length of the waves which are emitted from the sun, or in the frequencies with which they vibrate. Light waves are only about 1/50,000 of an inch long, and they vibrate very rapidly as compared to radio waves. In the terminology of radio, we can say they are electromagnetic waves of very high frequency. For discriminating between the various frequencies or wave lengths that are found in the sun's radiation, scientists make use of a special instrument called the spectroscope.

Everyone is familiar with the scintillating rainbows that may be made to dance about the walls or ceiling of a room through the movement of a piece of cut glass held in the sunlight. Every one of these rainbows results from the fact that the glass through which the sunlight passes refracts or bends these waves in a

way which depends upon the number of vibrations per second in the various kinds of light waves that strike it. Sunlight, which we ordinarily speak of as white light, in reality consists of waves of many different frequencies. The waves that are vibrating most rapidly are those which are bent most. We recognize them as blue light. Those which vibrate a little more slowly come through as green, or if more slowly yet, as yellow light. The slowest vibrations to which the eye is sensitive are those which give us the sensation of red.

Each one of these little rainbow-colored bands constitutes a spectrum of the sun, and we may think of the cut glass as an analyzer of the sunlight. Every one of the colors extending from the red through the orange, yellow, green, blue, and violet has a wealth of meaning. A device which will show us a spectrum of this sort is in a sense a spectroscope. Scientists use this principle in constructing an instrument especially adapted for analyzing sunlight and actually measuring the various lengths of waves in the solar spectrum.

In a real scientific spectroscope, a carefully made prism of glass takes the place of the cut glass object in our homely illustration. There are usually various kinds of lenses employed to increase the intensity of the light and to magnify the details. Usually a very narrow slit is employed to restrict the sunlight as we examine it. Such a slit makes it possible to detect any absence of light of certain wave lengths in the spectrum. This tells us what frequencies are lacking as the light leaves the sun, and also reveals the wave lengths in the radiation that are absorbed in transversing the earth's atmosphere. We can think of each of the colors represented, and every gradation of color, as a result of particular frequencies with which vibrating atoms on the sun send out radiation.

To appreciate how rapidly light waves vibrate as they produce the different colors of the spectrum, let us examine a few illustrations of vibration.

The pendulum of a clock vibrates to and fro. If it is a grandfather's clock, the probability is that it goes over and back, completing one cycle in two seconds. The electricity that lights the lamps in our houses, heats our flatirons, runs the refrigerator or vacuum cleaner, in most communities consists of vibrating pulses. These pulses are now generally standardized at sixty cycles a second. The filament in your desk lamp is heated by these electrical pulses. The pulses are so rapid that the hot filament in the electric bulb does not have time to cool off perceptibly before it is heated again. Thus the lamp sheds a continuous uniform light with the absence of flicker. In earlier days, some commercial circuits operated at a lower frequency. If the frequency of the current is as low as thirty cycles per second, a perceptible flicker is noticed, for an electric lamp on a thirty-cycle circuit has a perceptible moment in which to cool off a bit before the next electric pulse brings it back to its former brilliancy.

When you listen to your favorite program over the radio from a commercial broadcasting station, the radio waves strike the antenna of your receiving set from somewhere between 550,000 and 1,500,000 times per second, depending upon the station to which you may be tuned. If you set your dial, for example, so as to receive the program from the WBBM Air Theater at Chicago, you make the setting 780 kc. as listed in the radio page of your newspaper. A "kc." or kilocycle is the name for 1,000 cycles. The vibrating waves coming from Chicago, therefore, pulse 780 thousand times per second.

When we look at the solar spectrum through a spectroscope, the light at one end of the band producing the sensation of red vibrates 400 million million times per second. When we look from the red toward the green and blue end of the spectrum, the frequencies of these electrical waves of sunlight increase until we see the deep violet hue at the extreme end of visibility. Here the number of vibrations per second is 800 million million,

or a frequency about double that of the light at the red end.

There are still light waves of higher frequencies out beyond the violet to which our eyes are not sensitive but which will readily affect photographic plates. These are the ones that give us sunburn. This is the region that we call ultraviolet because it is literally out beyond the violet. Much of this ultraviolet light is a dangerous form of radiation, but fortunately most of it is absorbed by the earth's atmosphere before it reaches us. At the top of the atmosphere, say one hundred miles up, this intense ultraviolet light electrifies the molecules of oxygen and hydrogen and forms a conducting ceiling from which radio waves are turned back to earth, thus making long distance radio communication possible. We shall have more to say about this later, and we shall see how this radio ceiling is affected by sunspots.

It is rather intriguing to think that this very important part of the solar spectrum, and the one which produces vitamins in plants and animals, is in the region of light which we cannot see at all. Perhaps we should call it dark light. Dark light would be rather too loose a term to apply to this region, however, for we have another region of dark light down at the red end of the spectrum. Out beyond the red there are vibrations in sunlight too slow to make any effect on our eye. It would be logical to call this region the ultrared. However, to avoid confusion with the ultraviolet, we call it the infrared region—that is, inside the red.

Thus we see there are two kinds of dark light; one beyond the violet, and the other inside the red. The relatively slower vibrations of the dark light inside the red we feel as heat. Isn't it curious to think that the eye, which is so sensitive an optical instrument that it can see very faint stars at night, completely falls down in detecting radiation which happens to be a little slower than 400 million million vibrations per second on the one hand, or a bit faster than 800 million million cycles per

second on the other hand? Yet our skin, so to speak, picks up these waves where the eye leaves off. The fact that we sunburn shows that our skin responds readily to the dark light of ultraviolet radiation. At the same time, our skin readily perceives heat. We feel the warmth from the sun in another region of the spectrum which our eye cannot see. This is due to the fact that the solar vibrations from the infrared are absorbed by the skin and transmitted by infra rays to our nervous system, producing the sensation of heat.

While the eye, in a sense, is a truly beautiful instrument, it is really very limited in its range. The range of the eye, to use a musical analogy, is only one octave. The average ear on the other hand is sensitive to about eight octaves of the musical scale. Were we to depend alone upon our eyesight for analyzing radiation from the sun, we should never know that the sun sent out vibrations at all covering more than the one octave of the visible solar spectrum. Fortunately, very sensitive devices can be made that will detect the energy that is vibrating either too slowly or too rapidly to be seen by the eye.

One of these devices is the photographic plate which picks up the higher frequencies, and the other is some form of a heat-measuring instrument which will detect the slower vibrations inside the red end of the spectrum. The photographic plate may be made fairly sensitive to the whole visible region of the spectrum and also for a considerable distance into both the ultraviolet and the infrared. When we use a photographic plate in connection with the spectroscope, we can get a map of the effects of the radiation from the sun over a very large range of frequencies all at one time. Of course the photographic plate does not show us the beautiful rainbow colors of the spectrum, but the photographic emulsion on the plate darkens wherever the vibrating radiation from the sun strikes it. The more intense radiation blackens the plate heavily; less intense radiation blackens it but slightly. With a spectroscope and a photographic plate we can

learn much about the quality and the intensity of sunlight over a very wide variation of frequencies.

In a professional spectroscope, the sunlight falling upon it is intercepted by a very narrow slit which forms a part of the optical system of the spectroscope. This slitlike window restricts to a hairline the illumination falling on the spectroscope. When we look at the resulting spectrum of sunlight, or when we photograph it, it is found that the banded spectrum is no longer a continuous blending of colors from red to violet. There are numerous little vacancies where the colored band is interrupted. These gaps give the impression of dark spaces or pencil lines crossing the colored band vertically.

From a long study of the kinds of light given out by the various chemical elements, we have learned how to interpret the meaning of these lines in the spectrum. We see that they are arranged in definite patterns. We have come to know that they represent certain missing frequencies in the scale of waves which come to us from the sun. Either these frequencies were never sent out from the sun's broadcasting station, or else they have been absorbed on the way.

Years of study and analysis of the solar spectrum give us the interpretation of these dark lines and bands where the continuous spectrum of sunlight is interrupted. The light from the brilliant surface of the sun has to pass through various cooler gases and vapors on the way. Most of these gases and vapors are really in the outer part of the sun. The sunlight, passing through clouds of hydrogen, sodium, calcium, and many other elements, has had to pay transit charges to each of the little atoms of these elements in order to pass. Each particular element imposes its own protective tariff on that particular kind of vibration which its own radiating machinery might have manufactured. After sunlight has passed through ninety-three million miles of intervening space, it again must transverse the earth's atmosphere where molecules of oxygen, nitrogen, and water vapor again take

their toll before allowing the sunlight to pass earthward. These familiar gases in our atmosphere again extract their quota and produce dark lines in the spectrum of the sun. Those who have worked with spectroscopes know, therefore, that these dark lines represent the absorbing power of the sun's atmosphere and that of the atmosphere of the earth. The positions of the lines portray characteristically the various chemical elements which came in for their share of the wealth of radiation of the sun before the sunlight was allowed to pass to the surface of the earth.

With the radiation of the sun sorted out in this fashion, it becomes easy to study the quality of sunshine and detect any change in its intensity or in the absorbing powers of the atmosphere with changes in the season and in the sunspot cycle.

In 1924, one of America's foremost astronomers began systematic measurements of the amount of ultraviolet light in the solar spectrum received at the earth. From such measurements it was hoped that science might ultimately be able to decide the question as to whether the intensity of ultraviolet sunshine changed from year to year, and how much the variation in its intensity might really be. This astronomer was Dr. Edison Pettit of the Mount Wilson Observatory of the Carnegie Institution of Washington. Dr. Pettit had been working for a number of years to develop a simple but sensitive mechanism which would measure this energy. Knowing that the vibrations of sunlight, no matter what their wave length or frequency might be, have a certain amount of energy in them that can be turned into heat when they strike an absorbing surface, he determined to utilize the heat coming from the ultraviolet rays to generate electricity. Then with a suitable measuring instrument for the electric current resulting, he could tell just how intense was the ultraviolet light which he was measuring.

Did you know that the warmth of your fingers can be made to generate an electric current? Take a piece of copper wire and a similar piece of iron wire. Twist this pair of wires together at

each end. If you hold one of the junctions between your fingers, which are at blood temperature, and leave the other junction exposed so that it will be no warmer than the temperature of the room, an electrical current will flow through the loop you have created, due to the fact that one end of this pair of wires is warmed by your fingers over and above the temperature of the other end. If you were to connect a sensitive electric meter into the circuit, you would see that there is a current flowing in the wire, and you could measure its strength by the reading of the meter. Any two pieces of wire of unlike material will do the trick, but some combinations are much more effective than others.

Dr. Pettit knew this, so he took a piece of bismuth wire and silver wire and joined the ends. To make the affair sensitive, he used tiny little bits of wire which would respond very quickly to changes in temperature of even a few thousandths of a degree. With a very sensitive meter connected into the circuit, he could measure the actual difference in temperature between the junction which he exposed to sunlight and the one end which was left shielded from the sun's radiation.

It was then only necessary to devise some screen or filter which would cut out all of the sunshine except the ultraviolet light. For this he selected a thin sheet of silver. Probably it never occurred to you that silver will let light shine through it. If the silver sheet is thin enough, however, ultraviolet light will go through, whereas ordinary light will not be transmitted at all. The sheet of silver which Dr. Pettit used was only about one-millionth of an inch in thickness. Yet this thin film of silver for transmitting ultraviolet rays from the sun would stop all other kinds of light from getting through. So he arranged his little thermoelectric battery, or thermocouple as he called it, so that when the sun shone the ultraviolet light would be transmitted by the silver screen to his recorder. The meter which he used to record the amount of electricity generated would thus

give the measure of the intensity of the ultraviolet light shining into his instrument.

Of course, some days sunshine may be brighter than on other days, owing to haze in the earth's atmosphere. So he arranged to compare the readings through the silver screen with similar readings made by sunlight shining through a very thin film of gold. He selected gold, for gold lets through only a very narrow strip of green light in the solar spectrum, a region which he believed would vary very little compared with the variations he hoped to measure in the ultraviolet.

Every day, beginning in 1924, Dr. Pettit's apparatus measured the strength of ultraviolet light as compared with the amount of green light in the solar spectrum. He found variations as much as 30 per cent. The ultraviolet light increased greatly in its intensity with the rise in sunspot numbers from 1924 to 1927. It was also very high in 1929, when once more sunspots were numerous. As sunspots decreased in number, the ultraviolet light decreased again. As a result of Dr. Pettit's work and measurements made elsewhere in the world, we feel that there is now a scientific basis for believing that the ultraviolet radiation from the sun is stronger during the years of sunspot maximum than during sunspot minimum. There have been, however, some discrepancies in the measured results. During the sunspot maximum in 1928, the ultraviolet light as measured by Dr. Pettit's instrument fell off to a value nearly as low as he obtained in 1924 when he began his observations. This does not necessarily mean, however, that the actual strength of the ultraviolet rays sent out by the sun was less in 1924 than in 1928. It may very well be that some of these shorter light waves were absorbed at the time in the upper atmosphere of the earth, and thus did not get through to his measuring apparatus.

Up above the stratosphere there is a thin layer of ozone which scientists believe is produced by the ultraviolet light of

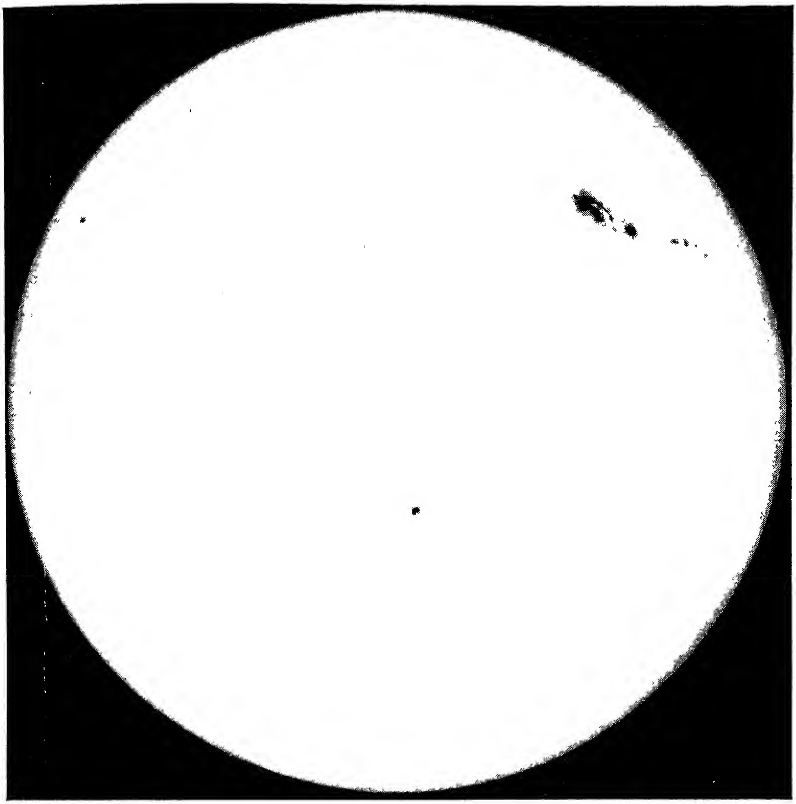


Plate I. The largest sunspot on record. (Photographed February 8, 1946, at the United States Naval Observatory.)

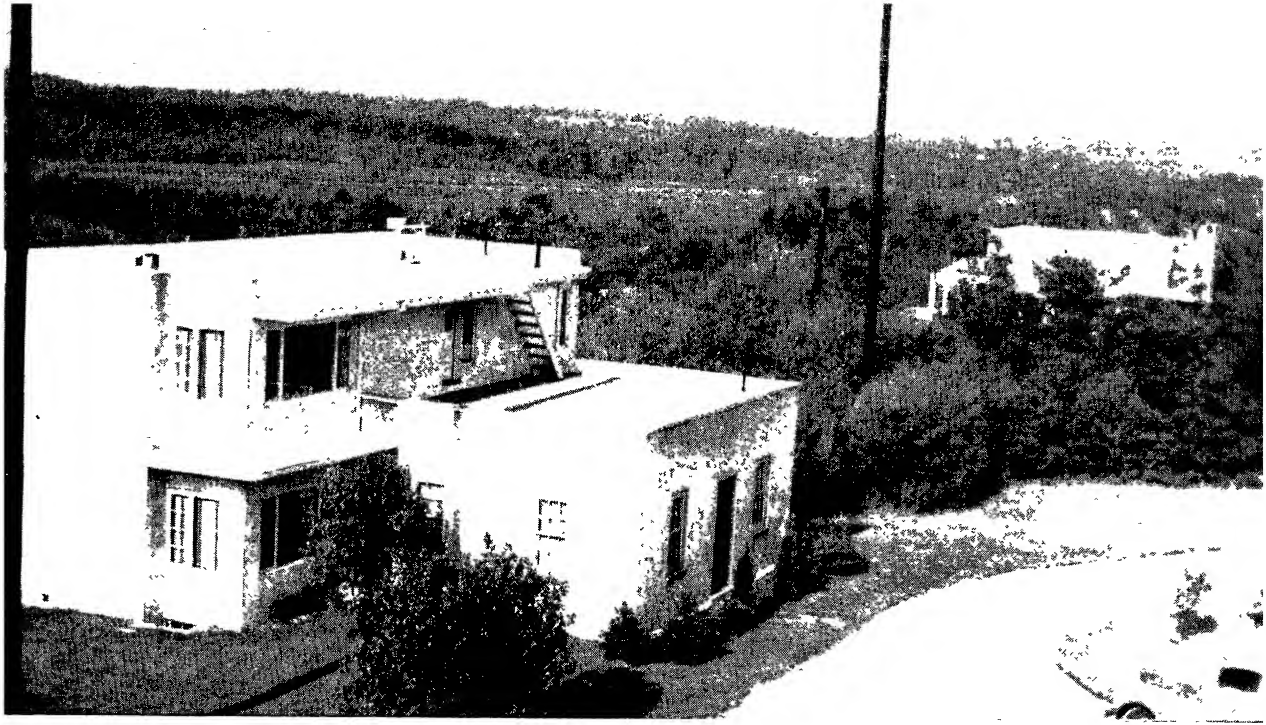


Plate II. Cosmic Terrestrial Research Laboratory at Needham, Massachusetts

the sun shining on the oxygen molecules of the air. As the ultraviolet light from the sun increases, more ozone will be formed. On the other hand, too much ultraviolet will again decompose the ozone. It is a fairly complicated process. However, when the oxygen goes to form ozone, it is at the expense of ultraviolet radiation. Thus the amount of ultraviolet light from the sun used up in making ozone will never reach the earth's surface at all. Moreover, the thicker the ozone layer, the more ultraviolet radiation is absorbed in it. So you see that during 1928, when the sunspots were most numerous, the intensity of the ultraviolet rays from the sun may have been so great as to create a very thick layer of ozone in the upper atmosphere, which in turn would cut off from the earth's surface a great deal of this ultraviolet radiation that was actually responsible for the increased ozone. This may be the explanation as to why there was a drop in the amount of ultraviolet radiation measured by Dr. Pettit's apparatus just at the time of sunspot maximum, when we might have expected the greatest amount to be recorded.

When the sunspots subside, it seems quite likely that the sun sends us less ultraviolet light so that the rate of production of ozone in the upper atmosphere of the earth will, in general, follow a decline in the sunspot curve. If the ozone layer, however, thins very much, it will be less efficient in screening the ultraviolet rays from the surface of the earth. So, we momentarily find in Dr. Pettit's measures that there will be times when the ultraviolet light seems to grow stronger at sunspot minimum, for ozone rapidly decomposes unless the supply of ultraviolet rays from the sun is kept up.

We see, then, that there are causes for many variations in Dr. Pettit's measurements so that one cannot expect too close a correspondence between sunspots and the amount of ultraviolet radiation that may be measured in any given place at any one time. One thing, however, is very important, and that is that

the measurements made by Dr. Pettit at the Mount Wilson Observatory should give an exact indication of the amount of ultraviolet sunshine that came through the atmosphere during the years of his observations. After all, it is the quality of the sunlight that reaches the earth's surface that is important to us and to all growing things.

Owing to the important bearing ultraviolet sunshine may have upon human health, the Desert Laboratory in Tucson, Arizona, set up one of Dr. Pettit's instruments. Often discrepancies were observed in the readings at Tucson as compared with those made at Pasadena. This was at times discouraging. However, it seems not improbable that clouds of ozone may be formed over different regions of the earth, and that the variability of ozone absorption may account for some of the discrepancies. It is unfortunate that in the early 1930's these observations were abandoned because of such discrepancies, and that a long series of constant observations has been broken. It would be very desirable if additional measurements of ultraviolet light could be continuously carried on in various parts of the earth. It is quite likely that the atmosphere of the tropics may behave differently in the screening of ultraviolet light from that of the temperate zones. Certainly, as we shall see later, radio observations indicate that far above the surface of the earth there is a great amount of variation in the ultraviolet radiation of the sun. It is much more intense at sunspot maximum than at sunspot minimum.

Another man who has long been measuring solar radiation because he believes it important to mankind is Dr. C. G. Abbot, until recently Secretary of the Smithsonian Institution in Washington.

In his early days Dr. Abbot was intimately associated with Samuel Pierpont Langley, a predecessor as Secretary of the Smithsonian Institution. Langley was a great student of the sun. With a sensitive electrical instrument he was one of the first

to explore the energy throughout the whole solar spectrum. He believed that the amount of heat and light the sun sent to us was not constant but varied from year to year and perhaps even from day to day. Langley thought that if one were to measure the total amount of heat and light from the sun systematically, year in and year out, one would find not only that the amount of radiation from the sun varied but that this variation in the heat from the sun would prove to be a very important factor in forecasting the weather weeks and perhaps even months ahead. It was therefore natural that Dr. Abbot should carry on the project visualized by Professor Langley.

For nearly fifty years now Dr. Abbot has been measuring the change in total energy that comes from the sun, and daily exploring the solar spectrum. He developed a special instrument which would convert all of the energy in sunshine into heat. He calls his contrivance a pyrheliometer, which literally means a meter for measuring the heat of the sun.

This device consists essentially of a small circular box closed on all sides and having a blackened silver disk for a top cover that may be exposed directly to the sun's rays. The little circular box is filled with water into which is inserted the bulb of a thermometer with the stem extending outward. This simple little affair is mounted in a convenient way mechanically, so that it can be turned readily to allow the sun's rays to fall perpendicularly on the surface of the box. There is a shutter something like a camera shutter which may be opened or closed to admit the sunshine to the water cell.

Every day this instrument is carefully pointed at the sun, the shutter is opened, and sunshine is allowed to fall on the container for one minute. Sunshine striking the blackened silver disk is turned into heat which warms the water within. The thermometer records the rise in temperature of the known amount of water as it is warmed during the minute in which the sun's heat is allowed to fall upon the instrument. From the rise in

temperature of the water, the total amount of energy in the sunshine can be readily calculated.

It is found that the average amount of radiation from the sun is 1.94 calories per square centimeter per minute. The calorie is a unit of heat familiar to all engineers. It represents the amount of heat necessary to raise the temperature of one gram of water one degree Centigrade. The value which Dr. Abbot has obtained from many many thousand measurements of the heat of the sun is generally adopted as the "solar constant." It was originally thought that the sun's heat was indeed constant. On the other hand, Dr. Abbot's measurements show that it may vary from time to time as much as 4 per cent. Even this small amount of variation in the sun's radiation, he believes, is largely responsible for our changes in weather, and could we predict accurately the variation in the sun's radiation, we should have a more reliable means for making long-range weather forecasts.

Dr. Abbot has been most interested in endeavoring to learn how to forecast weather from the changing values of the solar constant which he has been measuring every day at three different stations scattered about the globe and maintained by the Smithsonian Institution. The odyssey of Dr. Abbot for this purpose has been most fascinating. This persistent scientist has circumnavigated the globe seeking ideal locations for his service stations. In order to make observations most effective, it is necessary to observe the sun every day in the year. This necessitated seeking places where sunshine was as little interrupted by cloudiness as it was possible to find. It was also necessary to find locations as much devoid of moisture as possible because moisture in the air absorbs much of the sun's heat. To minimize these difficulties, he has therefore established his observing sites in high, desolate, arid regions. One of these is Table Mountain in California; another is at Mount Montezuma in Chile; and the third is located on Mount Sainte Katherine in Egypt, not far from Mount Sinai, famous in Biblical literature. Dr. Abbot

has found surprisingly close accordance in the observations made from these widely separated stations. In addition to the readings made with his carefully devised pyrheliometer, a part of the program is to daily explore the energy throughout the whole solar spectrum at each of these stations in order to find out how much absorption has been introduced by the earth's atmosphere, and to determine the correction factors for this so as to make more reliable the resulting values of the intensity of the solar heat arriving at the top of the atmosphere of the earth.

Dr. Abbot has suggested the desirability of sending his apparatus into the stratosphere suspended from balloons. At such high altitudes, with 95 per cent of the earth's atmosphere below, the apparatus would then be in a position to get measures of ultraviolet radiation from the sun in a way that cannot be done at any station on the surface of the earth. It seems reasonable to suppose that if such a venture were to be carried out, we would find a closer relationship between the sun and the weather than has yet been discovered.

Since life on the earth is so dependent upon the weather, one can at once see the value of careful measurements of sunlight continuously maintained day in and day out and year after year. It is only when we have a sufficient accumulation of scientific records of this nature that we can hope to solve some of the unsolved questions in meteorology today.

Chapter 4

SUNSPOTS AND RADIO COMMUNICATION

I HAVE BEEN talking with an associate who has just returned from a scientific mission in Europe. His plane was delayed two days in crossing the Atlantic on account of sunspots. The connecting link between sunspots and air traffic is not so remote as one might think. Air traffic is dependent upon maintaining radio communication between base stations and the plane aloft. Without the aids to aeronautics which have developed around radio, a transoceanic flight would still be a serious adventure. Planes would be continually confronted with unanticipated hazards of weather, navigation, and landing at their destinations. Sunspots can seriously interfere with radio communications for the reason that they upset the electrical balance of the upper air through which the magic waves of radio are transmitted over long distances from one place to another. With the increase in sunspots during the past two or three years, it has been a frequent occurrence to read in the headlines of our morning newspaper, "Sunspots Blot Out U. S.-Europe Radio"; "Record Sunspot Upsets World Communications"; "Sunspots Jam Radio—Delay Ocean Planes"; "Sunspots Cause Phone Failures Across the Atlantic"; and similar headlines recently culled from our national dailies.

In order to appreciate something of just how sunspots interfere with radio communication, we need to take a cosmic look at a cross section of the earth's atmosphere through which the radio waves travel. (See Plate III). As is very generally known, the air at the surface of the earth exerts a pressure of about fifteen pounds per square inch, corresponding to a baro-

metric pressure of 29.5 inches or 760 millimeters of mercury. This pressure varies somewhat from day to day depending on the vagaries of weather, but such is the average value that has been adopted for standard conditions of the atmosphere at sea level. When we make an ascent in an airplane this pressure rapidly diminishes, as anyone who has flown, well knows. At an altitude of three miles or 15,000 feet, half of the earth's atmosphere is below us and the barometer in the airplane has fallen to about fifteen inches of mercury or 380 millimeters. Above this level the atmospheric pressure continues to decrease rapidly, and at a height of thirty miles the mercurial barometer would register two millimeters. At one hundred miles, the air is so thin that it has been estimated that the atmospheric pressure is but one millionth of even this low value. Nevertheless, this thin atmosphere is populated with millions and millions of molecules of oxygen and nitrogen flying about like tiny bees loosed from a hive. Each one of these little molecules is in turn composed of atoms.

In this atomic age it is hardly necessary to tell that the atom itself is composed of positive and negative charges of electricity. Atoms also contain other tiny particles that belong to neither of these two parties, and because they are quite neutral in their cosmic affiliations, they are termed *neutrons*. Every now and then, the little negative electrons, circulating about the nucleus of the atom somewhat the same as the planets circulate about the sun, become completely detached from the atom. When such a detachment takes place, we commonly say that the atom has become ionized. The cause of this detachment, or the ionization of the atom, is chiefly due to the action of the ultra-violet light of the sun shining on the top of the atmosphere. These ionized particles or ions render the air electrically conducting. This makes possible the long-range propagation of the electromagnetic waves sent out from the radio antenna where signals or messages are broadcast.

The waves emitted from a broadcasting antenna spread out in all directions like ripples caused by a stone dropped into a pond or lake. Some of these ripples or waves travel directly over the surface of the earth or ground. These are called the ground waves. They do not travel very far and may completely vanish a few miles from the transmitter of the radio station. The waves, however, that travel upward, known as the sky waves, meet a spherical shell of ionized particles at about seventy miles above the surface of the earth. Just why there is a stratification of ionized particles at this particular height no one yet knows. However, this stratified shell of ions is highly conducting electrically and forms a reflector from which radio waves are turned back to earth very much as the ceiling of a squash court bounces back the tennis ball that is directed to it. It is this particular electrified ceiling of the upper air that is responsible for the transmission of all our radio music from distant stations broadcasting in the familiar broadcast band. At a height of about one hundred fifty miles, there is another region in the upper atmosphere where the electrical ions are concentrated, and radio waves that are too short to be reflected from the first layer will be turned back from this second ceiling. The waves reflected from this region are those used in ordinary short-wave reception of a frequency, let us say, of from five to thirty megacycles. A megacycle is a million cycles per second, or the equivalent of a thousand kilocycles per second.

As long as these radio ceilings are relatively stable, we can count on the return of the radio waves with reasonable stability and regularity. If, however, these radio ceilings become disturbed, the reflection may become very poor and the radio wave propagated through the sky may fail to return at all to the anticipated receiving station. Now there is a very direct connection between the appearance of spots on the sun and the upsetting of these ionized layers.

We have good reason to believe that electrified particles are shot out from the region of sunspots with very high velocities. When a cloud of these particles from the sun encounters our radio ceilings, the effect is a very serious disturbance in the reflecting surface. Reflections are irregular and confused, and we fail to receive messages sent out from distant broadcasting stations. Airplanes dependent upon radio communication remain grounded, and thus we see how sunspots can interfere with air travel.

There is also another kind of disturbance from the sun which may be anticipated with every rise in solar activity accompanying increasing numbers of spots seen on the solar surface. This other kind of disturbance is in the nature of a very intense blast of ultraviolet light emitted from the sun. It may last from a few minutes to an hour or more, dependent upon the size and duration of the solar catastrophe that caused it. This flare of ultraviolet radiation reaches the earth with the speed of light, or just eight minutes after the event happened on the sun. When this reaches the spherical shell of ions that we call the ionosphere, it so rapidly increases the population of the ions that the reflecting power of the radio ceiling is killed. The electromagnetic waves of radio are completely absorbed or otherwise fail to reach their destination until order is again restored in the ionosphere. This type of phenomenon occurs on the daylight half of the earth on which the sun is shining. Such disturbances are most common around noonday, or perhaps we should say between ten A.M. and two P.M. It is very valuable to science to record these occurrences, and there are now several laboratories cooperating with the National Bureau of Standards and other agencies where special apparatus has been installed for following all these vagaries of radio.

The apparatus used for measuring the strength of radio waves as they are received over a distance at any given place

is known as a field intensity recorder, for it actually records at any moment the strength of the electrical field caused by the electromagnetic waves of radio at any assigned distance. The Cosmic Terrestrial Research Laboratory (Plate II), associated with the Massachusetts Institute of Technology and located at Needham, Massachusetts, operates many such field intensity recorders. These tell just how strongly the radio wave is being received from a distant station throughout the entire twenty-four hours. In almost uncanny fashion the pen of the recorder slides to and fro along a roll of chart paper that slowly unwinds with the passing of each hour of the day. The movement of the pen to the top of the chart indicates that the strength of the radio wave received is increasing, while a movement in the opposite direction will show that it is fading or decreasing in intensity. When an ultraviolet flare takes place on the sun, accompanying sunspot activity, the pen will fall rapidly to zero on the scale, showing that no reception is received. When the worst of the damage is over, the pen will again start moving up, showing a gradual recovery of the radio wave as the ionized ceiling of the atmosphere begins to return to normal conditions following the blackout. A trace of one such fadeout that occurred on December 9, 1944, is shown in Plate IV, where reception from the radio transmitter at the National Bureau of Standards station near Washington recorded an abrupt change in the field intensity on that occasion. Curiously, a repetition of the disturbance took place at the same hour of the day immediately following. Just why such a repetition should occur, we do not know. Is it possible that a pencil-like stream of intense radiation from the sun was encountered by the Needham-Washington transmission path, which quickly lost its effect as the earth turned under this stream of radiation only to recur at about the same time the following day, when, by virtue of the earth's rotation, it again encountered the tail end of the same stream? On the second day following, no such disturbance

occurred, which might indicate that by that time this particular stream of radiation from the sun had ceased.

The first and most obvious effect of sunlight on radio reception can be observed by any radio enthusiast who goes gunning for a program from any distant station. Nearly everyone, who has not confined his listening to local programs broadcast from his own vicinity, knows that broadcast reception can be heard much better during the night hours than during the daytime hours. If the station is at a very great distance, say five hundred miles or more, it is very probable that it cannot be heard at all during the daytime. This is due to the fact that the strong sunlight of day over-ionizes the atmosphere, causing heavy absorption of the radio waves of broadcast frequencies in the lower atmosphere. As the sun goes down, however, the positive and negative particles in the air quickly recombine, reducing to a considerable extent this ionization. We then hear the distant broadcast station by reason of the sky wave reflected from the ionosphere seventy miles high. Good reception generally prevails throughout the night until the early morning hours, when shortly before sunrise the ultraviolet light of the sun again starts the process of ionization at high levels. This increases rapidly as the visible sun comes above the horizon, introducing heavy absorption of the electromagnetic waves, shown by the rapid diminution in the strength of the program received. A typical curve showing the increase of the field of WBBM, Chicago, broadcasting on 780 kilocycles and received at Needham, Massachusetts, is shown in Figure 1.

The intensity with which radio waves are received under normal conditions can vary very greatly, depending upon the distance between the transmitting station and the receiving set, and also upon the wave length or the frequency with which these waves are broadcast. Then, too, there is a marked seasonal variation which depends upon the length of the day and the intensity of the sunshine in producing the ions in the iono-

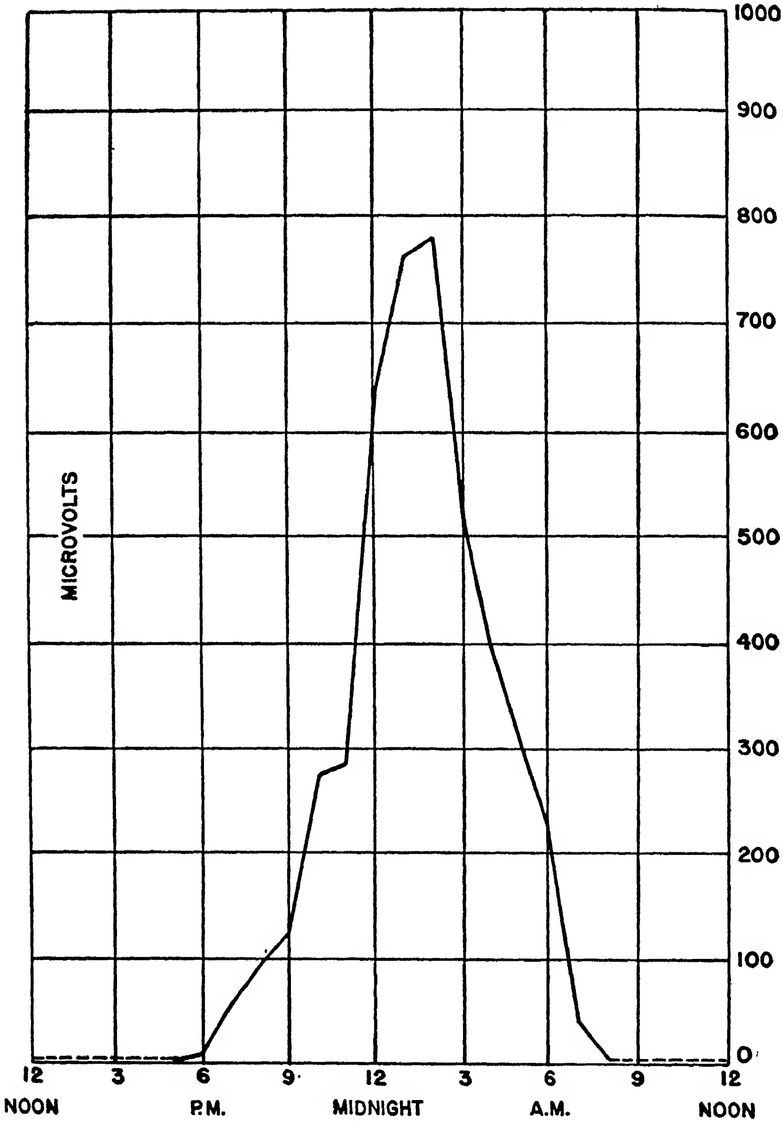


Figure 1. Diurnal change in field intensities of the WBBM broadcasting station, 780 kilocycles, Chicago, as received at Needham Laboratory

sphere. The curve in Figure 2 shows how the field intensities at nine o'clock at night vary throughout the year as received from Chicago on 780 kilocycles and observed at Needham. It is quite essential that we get a picture of the normal behavior of radio and its dependence upon sunlight in order to appreciate

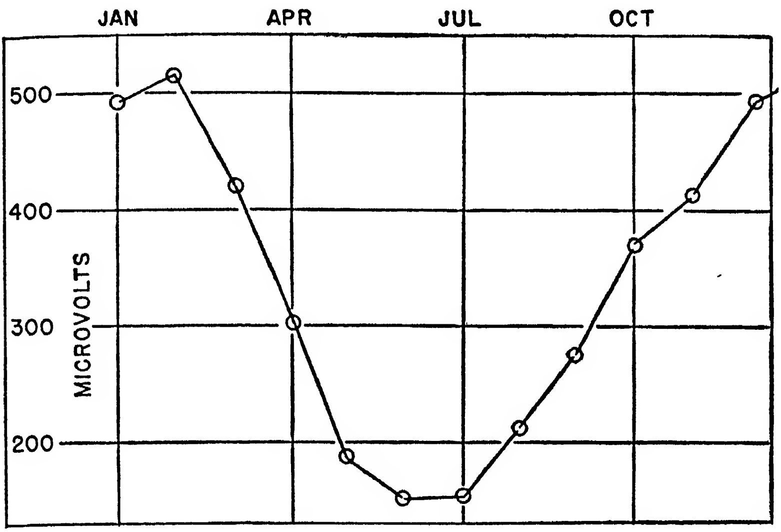


Figure 2. Seasonal variation in field intensities of the WBBM broadcasting station, 780 kilocycles, Chicago, as received at Needham Laboratory. Values taken at 9 P.M. E.S.T.

more fully how these normal conditions become abnormal with the breaking out of sunspots on the sun.

When we observe waves of much higher frequencies than those of the broadcast band, or, as is sometimes said, of shorter wave length, we find a quite different pattern. Figure 3, for example, shows typical reception of the 5-megacycle wave from WWV, National Bureau of Standards station at Washington, and received at Needham during the winter season. It will be observed that reception is relatively poor during the night and early morning hours, presumably due to an insufficient number

of ions to form a good reflecting ceiling. With the advent of sunrise, the ultraviolet radiation of the sun encounters the higher layer of the air one hundred and fifty miles high. The little electrons are rapidly bounced off from the atoms of oxygen,

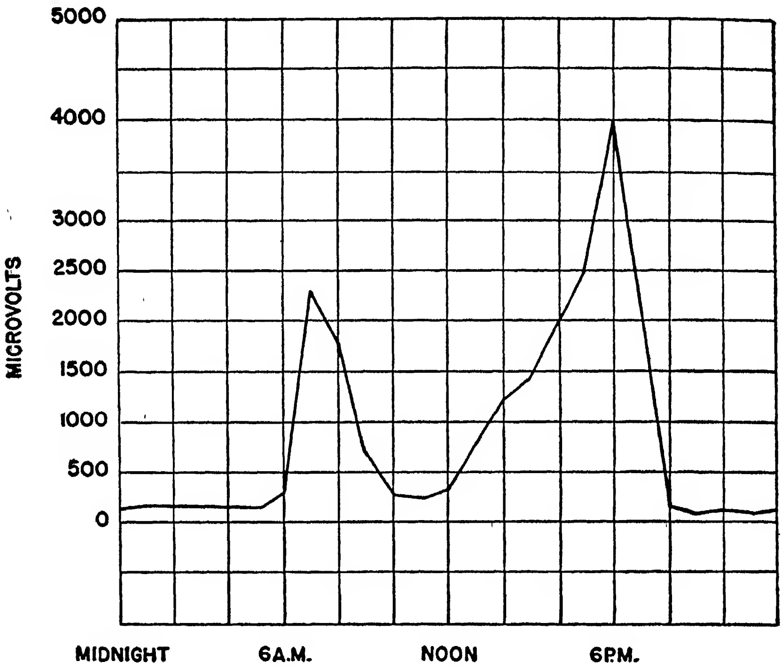


Figure 3. Daily variation in National Bureau of Standards standard frequency signal WWV, 5 megacycles, as received at Needham Laboratory, December 10, 1945

and ionization quickly takes place. With the improvement of the electrical conductivity of this upper air, the waves are better reflected back to the earth, and we see a sharp rise in the strengths of the field produced by these waves on the arrival at the antenna at Needham. With the increasing amount of sunshine as the sun rides high towards noonday, ions begin to form in the lower layers absorbing much of the energy in the

electric waves, so that the intensity received during the middle of the day rapidly diminishes. With the lower-slanting rays of the afternoon sun, the recombination of the positive and negative ions in the atmosphere takes place, reducing the absorption and again letting the radio waves from the high ceiling come through more perfectly. The reception rises, therefore, in the afternoon, and stays relatively high until after sundown. Following sunset, with the ultraviolet light of the sun removed, the ions in the reflecting ceiling combine and conductivity deteriorates giving us a poorer reflector again. The reflected wave again diminishes in intensity on this account, producing lower values in the strength of the field measured during the night.

We can see from Figure 3 that it is relatively easy to predict the time of day when we may expect the strongest fields of radio between Washington and Needham on the basis of the diurnal change that can be anticipated. Thus the two best times for communication under the conditions represented in the Figure are about seven o'clock in the morning and six o'clock in the afternoon. We should anticipate the greatest difficulty in communication to occur near noon and midnight.

Our long records of observation show us that this form of curve which is typical of the winter months is replaced by a very different type during the summer months when we have long days and more intense sunshine creating more than the average ionization. Figure 4, for example, shows the diurnal curve obtained on June 22-23, 1945. Under the conditions here represented, reception is high all night, due to a minimum amount of absorption of ions in the lower atmosphere. Reception deteriorates as soon as the sun comes up, giving lower values through the daytime with a minimum at noon. The field increases again as the sun goes down toward the western horizon. It is obvious that the sun is creating ions so rapidly during the summer daytime that we are experiencing a deterioration of reception due chiefly to the absorption of electro-

magnetic waves in the atmosphere. During the nighttime the recombination of these ions causes the absorption to very largely vanish, allowing the waves to come through relatively unimpeded from the reflecting ceiling, which still has enough ions

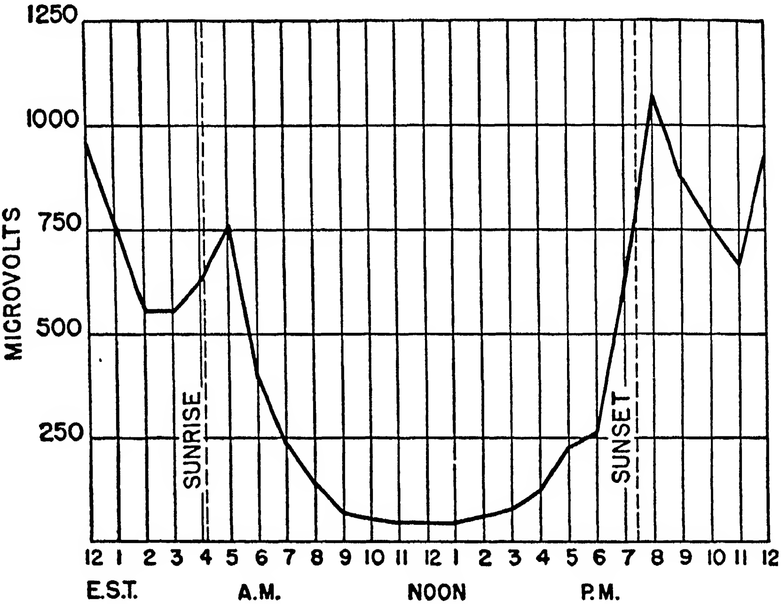
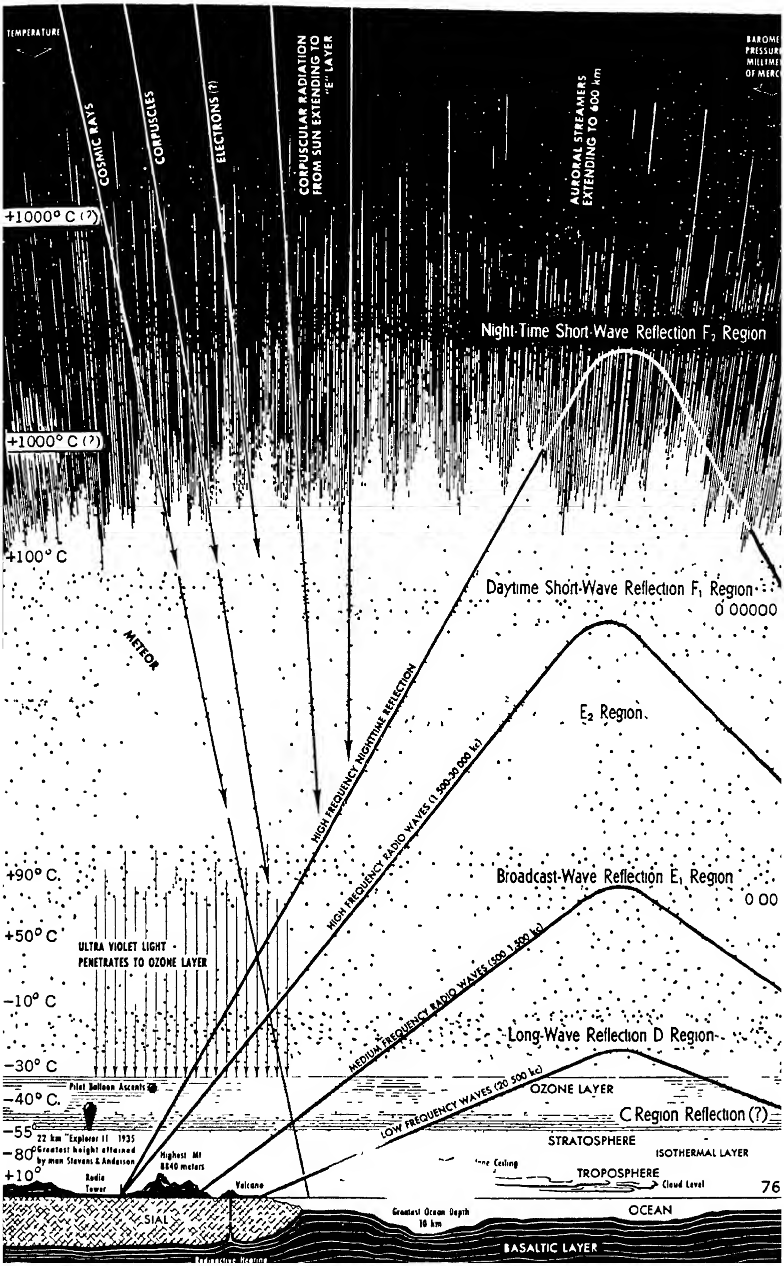


Figure 4. Daily variation in National Bureau of Standards standard frequency signal WWV, 5 megacycles, as received at Needham Laboratory, June 22, 1945

in it during the summer season to give good reception throughout most of the night.

During the rapid rise of sunspots in 1946, from a value of 47.6 in January to a value of 121.7 in December, a very remarkable change took place in the pattern of the Field Intensity records of WWV 5-mc. as received at Needham from Washington. The typical change from the summer to the winter type of the diurnal curve of field intensity did not materialize. The summer pattern of June, July, and August in 1946 persisted


TEMPERATURE
COSMIC RAYS
CORPUSCLES
ELECTRONS (?)
CORPUSCULAR RADIATION FROM SUN EXTENDING TO "E" LAYER
AURORAL STREAMERS EXTENDING TO 600 km
+1000° C (?)
+1000° C (?)
Night-Time Short-Wave Reflection F_2 Region
+100° C
Daytime Short-Wave Reflection F_1 Region
0 00000
METEOR
E_2 Region
HIGH FREQUENCY NIGHTTIME REFLECTION
HIGH FREQUENCY RADIO WAVES (1 500-30 000 kc)
+90° C.
Broadcast-Wave Reflection E_1 Region
0 00
+50° C
ULTRA VIOLET LIGHT PENETRATES TO OZONE LAYER
MEDIUM FREQUENCY RADIO WAVES (500 1 500 kc)
−10° C
Long-Wave Reflection D Region
−30° C
Pilot Balloon Ascents
−40° C.
OZONE LAYER
LOW FREQUENCY WAVES (20 500 kc)
C Region Reflection (?)
−55°
22 km "Explorer II 1935 Greatest height attained by man Stevens & Anderson
−80°
STRATOSPHERE
ISOTHERMAL LAYER
+10°
Highest Mt 8840 meters
TROPOSPHERE
Cloud Level
Radio Tower
Volcano
76
SIAL
Greatest Ocean Depth 10 km
OCEAN
BASALTIC LAYER
Radioactive Heating

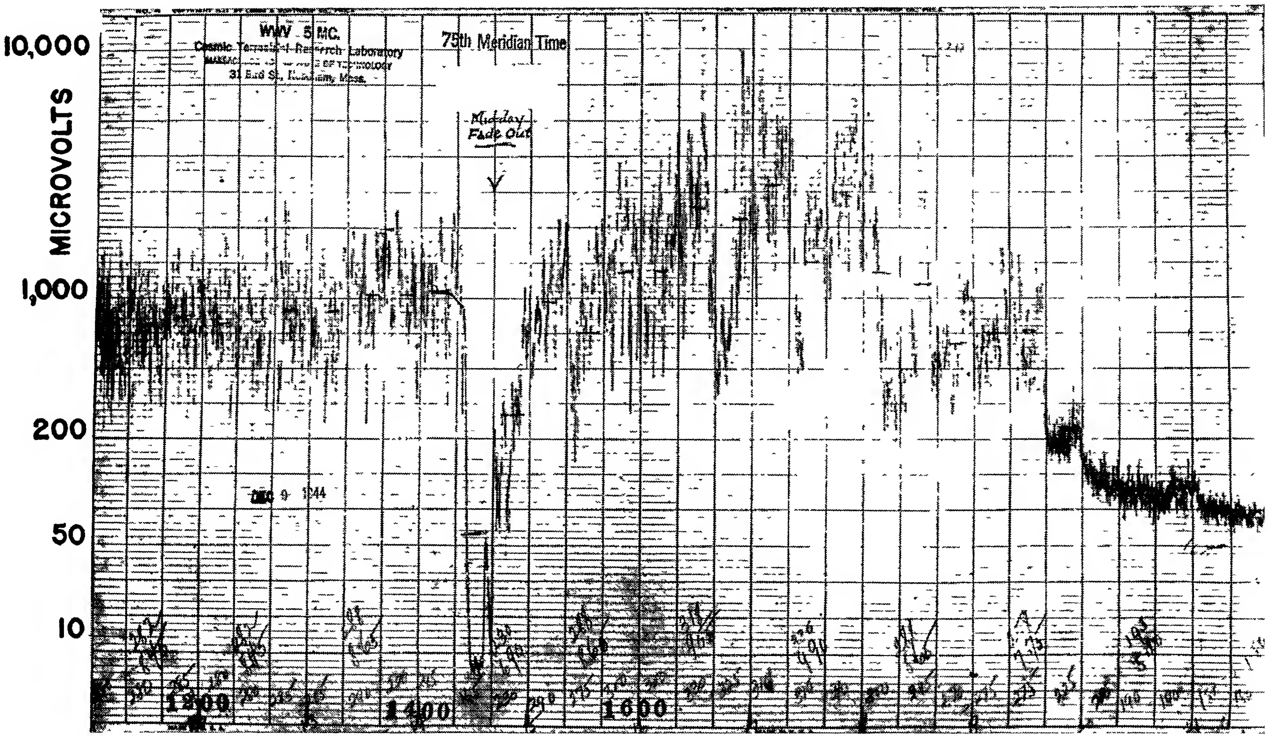


Plate IV. Record of radio fade-out recorded at Needham, Massachusetts, December 9, 1944

throughout the remainder of the year and even into January and February of 1947. The monthly curves showing the twenty-four-hour averages of reception for November-December, 1946, were very nearly the same as those for the summer months of 1946. The summer type, it will be recalled, consists of a strong night field of 1,000 microvolts or more, followed by fading after sunrise to a minimum near noon; then, as sunset approaches, a subsequent recovery to the high night field. It is believed that the explanation for the failure of the return to the winter pattern of low night fields, with morning and afternoon maxima, resulted from the increased ionizing radiation of the sun, concomitant with an unusually rapid rise in solar activity. Thus it appears that the increased ionization of the upper atmosphere during the sunspot rise of 1946 more than offset the effect of shortening days and lower solar altitudes that would have otherwise resulted in the anticipated transition to the winter type of reception curve.

When sunspots break out we picture a stream of electrified particles emitted from the sun that on reaching the earth produces two effects. One effect is that these particles disrupt very much the reflecting layer so that reflection becomes less regular, and second, that they create heavy ionization in the lower layers which rapidly absorbs the energy from such radio waves as are reflected back to earth. The result is a considerable interruption to radio communication on almost all frequencies. Long-continued observations at the Cosmic Terrestrial Research Laboratory have shown that, in general, the appearance of sunspots affects the highest of the radio ceilings first. Engineers call this the F layer. Short wave communication via the F layer is therefore the first to be seriously interrupted.

About a day after the greatest damage has been done to the F layer, the lower layer, known to radio engineers as the E layer, is most seriously damaged, causing interference in receiving radio programs over a long distance in the broadcast band.

After the disturbance on the sun has passed, the upper, or F layer, first recovers to normal conditions. The lower, or E layer, may stay disturbed for several days so that broadcast reception takes a much longer time to recover at these lower frequencies than does reception by way of the shorter waves or higher frequencies. A very violent disturbance on the sun, however, almost at once will affect both of these radio ceilings and the radio communication industry is for the time at a standstill. In such an event, however, it is usually the upper ionized region or F layer that is the first to recover and support normal reception. Several days or a week may elapse before there is again normal long-distance reception at broadcast frequencies at 550 to 1,500 kilocycles.

We must understand, of course, that all of this applies to distant reception, because it is only when one is concerned with radio waves coming from stations one hundred to one thousand miles distant that the sky waves of radio are utilized. If you live in the suburbs of Boston, New York, Chicago, or any other large city you usually seek your favorite newscast, music, or entertainment program from one of these near-by stations. Your reception in this case is concerned only with the ground wave which passes quite directly from the broadcasting antenna to your receiving set along the ground that separates these two points. In this case, the sky wave and sunspots are not involved.

Another effect is sometimes observed that can materially disturb your program reception if you live in the country, say fifty to one hundred miles from the broadcast station to which you are accustomed to listen. In such a position you may very well be receiving at times some of your program by way of the ground waves and some by way of the sky waves. When sky-wave reception is good, the stronger of these waves may destructively interfere with the ground waves and produce a certain mushiness or rapid fading of your program. When sunspots are numerous and the reflecting layer of the sky is badly

disturbed, thus reducing the intensity of the sky wave, you get your ground-wave reception without any such interference. In this case, local reception from a station not too far away may be actually better when sunspots are running rampant.

One must be careful not to generalize too widely, and glibly say that under all circumstances sunspots make for poor radio reception and a clear sun means good radio reception. It all depends upon the communication path involved, the length of the radio waves employed or their frequency, and whether or not you are beyond the radius of the ground wave when you tune in your program. In the case of long-distance radio such as transcontinental or transoceanic communication, the distances are too great ever to be concerned with the ground wave. Here the sky-wave transmission is of vital consequence. Thus, communication companies are intimately concerned with the cosmic effects on sky-wave propagation, conditions that are quite beyond man's control.

As we learn more about the method of propagation of radio waves and the effect of the sun on the ionized layers of the upper atmosphere, we can at least learn to anticipate the best communication conditions and to anticipate when long-distance radio communication may become quite impossible. During the war this was a matter of grave consequence, and a number of observing laboratories were constantly at work day and night watching these cosmic effects. At times the military departments would be warned in advance of probable days when communication to the European or Pacific theaters was likely to be difficult or impossible, and days when ideal conditions could be anticipated for the transmission of long-range messages and directives. Thus, even sunspots through their effect on radio were of major concern in an important phase of the war effort. Much of the information which can now be given had to be withheld during those years of national emergency.

Chapter 5

SUNSPOTS AND RADIO PREDICTION

We have seen in the last chapter how sunspots can seriously interfere with radio communication. The problems introduced are by no means simple, but we already know that the amount of interference depends upon the wave length or frequency at which a radio wave is broadcast, the time of day, the time of year, and also upon the number of sunspots that may be in evidence. How well the radio wave is propagated depends upon the number of ions that may exist at a given level at a given particular time. By knowing the state of the ionization of the upper atmosphere, we can better tell what frequencies or wave lengths should be employed to give the best possible communication over a given distance under such conditions of the atmosphere as may be encountered at a given day or hour. If there are not enough ions to turn back a radio wave of a given frequency or wave length, it is useless to employ a frequency higher than this. If legible messages are to go through, we must adopt such a frequency or wave length as we have reason to believe will be turned back to earth at the distant point at which we wish such a message delivered.

The number of ions in the atmosphere at any given time is dependent both upon the intensity and the duration of sunshine. This sunshine contains the ultraviolet light which is the principal agent in forming the ionization. If the ultraviolet light, as we have good reasons for believing, is more intense at the time when sunspots are most numerous than when sunspots are few and far between, then the ionization at a given time of day or season of the year will be accordingly greater during years of

maximum solar activity than during the years of low solar activity. Fortunately, it has been possible to devise means by which we can make samplings of the number of ions in the high atmosphere at any time of day or night, and from such samplings we may learn much that is helpful in the way of predicting the right frequencies to use for the best communication conditions at a given time.

The method now in general use at many ionospheric stations scattered over the globe is to send pulses of radio waves of varying length or frequencies directly upward and watch their return to earth in a very minute fraction of a second, when, as, and if they are returned. By changing the tuning of the sending apparatus, we can send out a constant stream of waves continually shortening as they proceed. Remember, as the wave shortens, the frequency or the number of its oscillations per second rises accordingly. If we begin with relatively low frequencies as radio waves go, we should have no difficulty in catching the return on suitable apparatus as the waves bounce back from the first ionospheric level, which we call the E layer. This you will recall is about seventy miles from the surface of the earth. Radio waves travel approximately with the speed of light, so that only a very small amount of time elapses between the time when a beam is sent up into the sky and when it bounces back to the surface. This interval of time is about 1/3,000 of a second. This is an inconceivably short interval but one which, with the modern technique of electronics, is very easy to measure indeed.

Now, if as these pulses of radio waves are sent upward, we gradually increase their frequency or shorten their length, an accomplishment easily done by adjusting the apparatus involved, we shall find that we arrive at a frequency sufficiently high, or a wave length sufficiently short, so that these radio waves will pass completely through the lower reflecting ceiling much as a ping-pong ball might pass through the coarse mesh of a tennis

net stretched overhead. If these waves pass through the E layer, they will travel upward to a height of one hundred and fifty miles before they encounter the F layer. Here the ionic concentration is much more intense, giving the effect of a screened ceiling of much finer mesh than that of the E region. Now the waves of a wave length too short (or a frequency too great) to be stopped by the E layer will be turned back by this second ceiling, the F layer. In this case we shall find that they are received back on our receiving apparatus with a delay of 1/1,500 of a second. This is about twice as long as the delay from the E layer. Remembering once more that radio waves travel approximately with the speed of light, we can calculate from the time elapsed in making the trip up and down the height at which they are reflected. This varies somewhat with the hour of the day, the time of the year, and also with the sunspot cycle. The lower, or E layer, varies very little in height, but the upper layer may change its height quite markedly.

Suppose, while our apparatus is still operating, we continue to increase the frequency, making the oscillations more and more rapid as the pulse is sent up. The waves accordingly will be getting shorter and shorter, and we shall arrive at a frequency where the waves are sufficiently short to penetrate this upper ceiling and be lost in space never to return to earth at all. This frequency at which the waves just fail to return from the ionized layer is known to radio experts as the "critical frequency." Without becoming mathematical, we may state that if we know such a critical frequency, we can readily compute the density of the ionic population of the ionosphere at the height of the radio ceiling. This becomes a very important element in the general theory of the prediction of the transmission of radio waves. When at a given time of day, for example, we find that a frequency of 10 megacycles becomes the critical frequency, we can see that it would be useless to try to use waves of any higher frequency in communication.

If we are sending our radio messages to some distant point, such as across the ocean, then the waves which may be reflected to the transoceanic station will arrive at the ionosphere much more obliquely and may be partially reflected, even though the frequency is so high that when sent vertically upward there would be penetration. Let us return to our analogy of a screen or net as the radio ceiling. We could have a net of sufficiently coarse mesh to allow a ping-pong ball thrown directly upward against it to pass through, whereas if the ping-pong ball were directed in an oblique fashion towards the net, it would be reflected. On this account, therefore, waves slightly shorter than those just necessary to pass through the radio ceiling, when sent vertically upward, may actually be turned back and be transmitted over great distances when directed obliquely. However, for better reception, the prognostication of the radio engineer would be to use frequencies of less than 10 megacycles.

The question of radio prediction, therefore, involves at once the size or the frequency of the waves that we use, the distance between the two points over which communication is to be established, and the density of the ionic population at the radio ceiling one hundred or two hundred miles high. We must remember that the density of the population of the ions in the ionosphere corresponds to the size of the mesh in our reflecting screen. Remember this changes with the time of day, the season of the year, and where we are in the sunspot cycle, since it is the radiation of the sun that is responsible for the creation of this ionized reflection layer that turns the radio waves back to earth. When the sun is in a disturbed condition and huge spots scar its surface, not only is the size of the mesh in our radio screen changing, but the screen is often undulating up and down, thus making any reliable reflection practically impossible. The general character of sunlight which, so far as radio is concerned, means the intensity at the ultraviolet end of the spectrum,

changes rather regularly with the coming and going of the sunspot cycle.

If day after day, month after month, we plot the observed critical frequencies at which radio waves fail to return to earth, we shall find a very close correspondence between these critical frequencies and the number of sunspots counted. The curve shown in Figure 5 shows the gradual rise of sunspots from 1934 to 1937, the subsequent decline to 1944, and the rise again in sunspot numbers to the present year. Below this curve of sunspot numbers there is shown, first, the critical frequencies for the F layer, or the upper radio ceiling of the earth's atmosphere. The next curve lower down represents the critical frequencies for penetration of the E layer or the lower radio ceiling from which waves of the ordinary broadcast frequencies are returned to earth. Both of these curves show a remarkable resemblance in form to the sunspot curve. The relationship of the critical frequencies in the E layer to the sunspots is so close that we can almost trace each irregularity in one curve with a similar irregularity occurring at the same time in the other curve. By the employment of such curves, we can see clearly the relationship of critical frequencies of both the E and F layers to the sunspot cycle. If we can anticipate the number of sunspots that may appear in any future year, we can anticipate the critical frequencies of that year, and therefore forecast the wave lengths or frequencies that should be used for communication purposes for, in general, the optimum reliable frequencies are well below the critical frequencies determined.

In practice, the calculation of the frequencies to use is fairly complicated. In the graph in Figure 5, the critical frequencies that are plotted are the average critical frequencies obtained between nine A.M. and three P.M. at Washington, and the curve has been smoothed by averaging twelve months at a time and moving this average ahead one month for each step. This is sometimes known as taking "running means" or "moving aver-

ages." When the ionic content of the atmosphere or the electron density of the ionized layers is low, as during the nighttime, the critical frequencies will be much lower than the average value. At noonday, when, due to strong solar radiation, the ions and electrons multiply in number, the critical frequencies will rise much higher than the average values shown in Figure 5. In Figure 6 is shown the actual change in critical frequencies

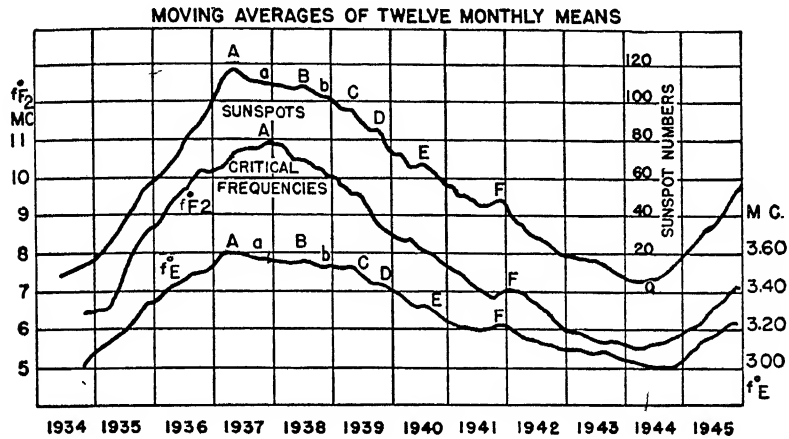


Figure 5. Sunspots and critical frequencies of the E and F layers

for the E layer during a twenty-four-hour day (August 1, 1937). This curve is drawn from data obtained from the Carnegie Institution of Washington, and based on measurements obtained at Kensington, near Washington, D. C. It will be seen that the lowest value occurs between three and four A.M., when 0.88 megacycle, or 880 kilocycles, is the frequency that will just penetrate the E layer at that hour. The highest value of 4.12 megacycles, or 41,200 kilocycles, was obtained near noon between the hours of eleven and twelve. Since usable communication frequencies are generally below these critical frequencies, it will be seen at once that the wave length or frequency to be used at noonday will be higher than that to be used

during the night hours. It must also be remembered that this curve (Figure 6) is the result for only one day's observation in August, 1937, and that the form of this curve will be different for different days. It will be much lower in the wintertime than

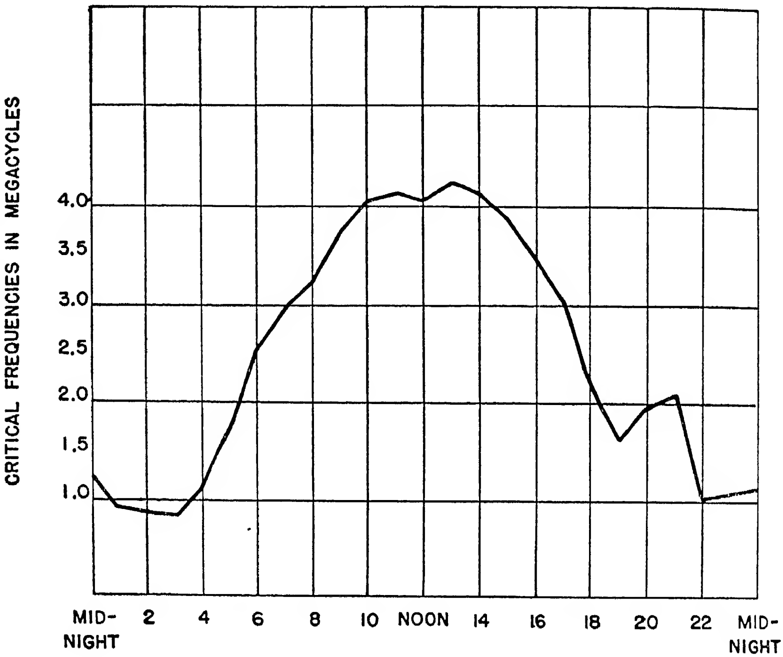


Figure 6. Daily change in critical frequencies of the E layer through twenty-four hours, August 1, 1937, at Kensington (Washington)

in summertime, for in winter the weakened sunlight fails to produce the large number of ions in the ionosphere that are found during the summer season when the sun is high and the days are long in the Northern Hemisphere.

Since communication companies must be ready to send messages to all parts of the world at all hours of the day and all seasons of the year, it has become increasingly important to have ionospheric stations for observing these critical frequencies scat-

tered over the entire globe. At present there are more than fifty such stations placed in strategic locations throughout the world. These are at one or more points in Newfoundland, Baffin Island, Canada, Alaska, the Continental United States, the West Indies, Peru, the Philippines, Hawaii, England, Norway, South Africa, Japan, China, India, the U. S. S. R., New Zealand and Australia. Additional stations are rapidly being inaugurated to supplement the data already being collected by those that are now in operation. Radio has become an international activity of first importance. Since the ionosphere covers the entire globe, the scientific problems concerned with the propagation of radio waves cannot be satisfactorily solved without the ultimate cooperation of all countries.

Even when we know the critical frequencies in the different ionic layers at different times of the day and seasons of the year, the actual problem of predicting how well a given signal will be received over a given path is still far from a satisfactory solution. Were radio waves from a given sending station subject to only a single reflection from the ionosphere, the problem would be more simple. When a radio wave is sent from Washington to Moscow, however, the ionosphere is not high enough to permit this wave to pass by means of a single reflection. We know that communication does take place between these two points and, therefore, picture that they must bounce back and forth several times between the sky and the earth before arriving at their ultimate destination. A radio wave may be sent from Boston to Chicago by a single reflection or, as is commonly said, by one hop. Such transmission is pictured in Figure 7. A wave, however, sent from Boston to arrive at the Pacific coast must be reflected once from the earth and twice from the ionosphere as shown in Figure 8. A wave which reaches Los Angeles from Boston will be reflected from the ionosphere somewhere east of Chicago, but that particular wave will not be heard in Chicago at all. This is not to say that a wave of a different frequency

from the Boston station traveling along a different path will not be heard in Chicago, for there is a reflection point about halfway between Boston and Chicago which may bring the wave down.

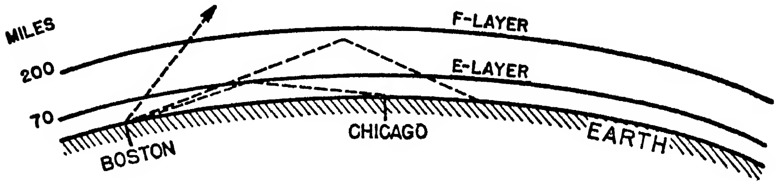


Figure 7. Illustration of radio transmission from Boston to Chicago by one reflection

How well a predicted wave actually arrives at a destination can best be determined by measuring the actual strength of the field at the point of arrival. This is why field intensity recorders are important, such as those in operation at the National Bureau of Standards, at the Cosmic Terrestrial Research Laboratory at Needham, at the Huancayo (Peru) Magnetic Observatory

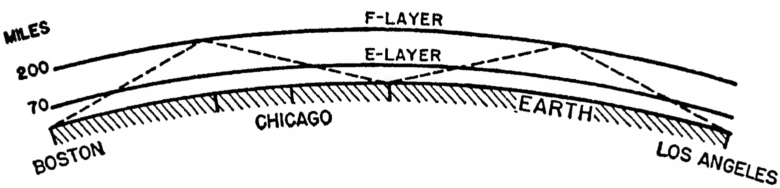


Figure 8. Illustration of radio transmission from Boston to Los Angeles by two reflections

of the Carnegie Institution of Washington, and at other cooperating institutions. It is customary to measure the strength of the arrival of a radio wave at a receiving station in terms of the electrical voltage which it will impress upon the receiving apparatus. At distances remote from the sending station, these voltages are very small and are measured in terms of millionths of one volt, such a unit being termed a *microvolt*. You

will recall that the voltage used on the usual domestic lighting circuits is 110 volts. The voltage given by an ordinary single dry battery such as runs your doorbell or lights your flashlight is one and one half volts. A microvolt is, therefore, less than one millionth of such a voltage furnished by a flashlight battery. Sometimes the so-called field of the incoming radio wave may rise on our recorders to one thousand microvolts or more. Such values are shown in the graphs depicted in Figures 1, 3, and 4. Less than one microvolt is scarcely detectable above stray noises that are always present in a receiving set.

Unfortunately the relationship between the strength of a received radio signal transmitted from a distance, and the critical frequency obtained from the ionosphere at that time, is not a simple one. The relationship, however, is more complex in the case of waves reflected from the F layer, that is, the high-frequency range, than in the case of waves reflected from the E layer, waves of medium frequencies.

It may be well at this point to list the somewhat arbitrary division of frequencies that have been adopted in a recognized classification by the Federal Communications Commission. This list covers the radio spectrum from wave lengths of thirty kilometers down to waves of but one centimeter in length ($0^{m}.01$), and is arranged in order of increasing frequencies.

Radio Frequency Classifications

Wave Lengths in Meters	Frequency in Kilocycles	Designation	Abbreviation	General Use
30,000-10,000	10- 30	Very low	VLF	Transoceanic
10,000-1,000	30- 300	Low	LF	Marine
1,000-100	300- 3,000	Medium	MF	Broadcasting
100-10	3,000- 30,000	High	HF	Amateur,+ Miscellaneous
10-1	30,000- 300,000	Very High	VHF	FM, Television
1-0.1	300,000- 3,000,000	Ultra High	UHF	Television
0.1-0 01	3,000,000-30,000,000	Super High	SHF	Radar

In addition to all of the complications in predicting radio communication just mentioned, it must be emphasized that sun-

spots play a very vital part, and that the fundamental relationships between radio frequencies and the numbers of sunspots shown graphically as in Figure 5 must be the constant guides through the years for all communication companies. The range through which they must operate their equipment depends upon the caprices of the sun. The Central Radio Propagation Laboratory at the National Bureau of Standards in Washington has evolved a workable formula that has proved its usefulness in making predictions several months in advance for transmission paths over all parts of the world. One of the most important factors in their formula is the number of sunspots, for the number of ions and electrons in the upper atmosphere can be pretty well determined from the state of solar activity represented by sunspot counts.

Of course, in a thoroughly satisfactory prediction, a communication engineer would like to know not only what frequencies or wave lengths may be anticipated to be received over a given path at a given distance, but how good will be the reception or how strong a field intensity, may be expected at a given time of day. One might suppose that the close relation between critical frequencies of the reflecting layers and sunspots would be indicative of a progressive change in the field intensities for a given frequency over a given path, with corresponding changes in the sunspot cycle.

Analysis of five-year records of the field intensities of WWV 5 mc. from Washington, as received at the Needham Laboratory, show that if we restrict the observations to the night hours, between 9 P.M. and 3 A.M., there has been a very marked increase in the field intensity with the rapid rise in sunspots during the last few years. From 1943 to 1946, measurements show that the field intensity rose from about 50 microvolts at the receiver to a value of nearly 1,000 microvolts at the receiver. This represents an increase of nearly twentyfold. Nighttime critical frequencies of the F layer measured in Washington

through the same hours rose from a low in January, 1944, of 2.5 mc. to values around 5 mc. in 1946 on the basis of a curve of twelve months' smoothed averages. It may seem surprising, at first, that if we consider the twenty-four-hour daily averages of field intensities measured at Needham throughout the same interval, there is little indication of any systematic change of field intensities with sunspots or critical frequencies. This, however, can be explained by the study of the daytime values of field strength measurements. These become increasingly lower during the middle of the day as sunspot numbers increase, on account of increased absorption by the daytime E layer, whose electron density, as shown by the critical frequency curve in Figure 5, increases rapidly with increasing numbers of sunspots. We may reach the conclusion, then, that as the sunspot cycle advances, day fields are lower while night fields are higher over the Washington-Needham path on the 5 mc. frequency. We see now, if we average all of the twenty-four-hour readings, how daylight fading offsets nighttime increases in field intensity, leaving us averages for the daily interval that vary little with sunspot numbers. The communication engineer, however, is especially interested in field values at particular hours so that he may direct his radio traffic accordingly.

Another element which frequently upsets predictions is the sudden appearance, usually during the night, of a cloud of ions over the communication path at the level of the E layer. No adequate explanation has been found for the occurrence of these ionic clouds which may cover a considerable area. By forming an unanticipated reflection layer at lower levels, they may suddenly increase the field intensity of the received radio signals. This often causes interference by bringing in unwanted stations that normally would not interfere. The occurrence of such a formation of ionic clouds in the E layer has been termed "sporadic E." An exhibit of the effect of such a "sporadic E" in recording the field intensity from the Bureau of Standards

Station WWV, broadcasting at five megacycles, is shown in Figure 9. Normally, during these night hours, we should expect low reception. It will be observed, however, that shortly after midnight there is a very strong increase in the strength

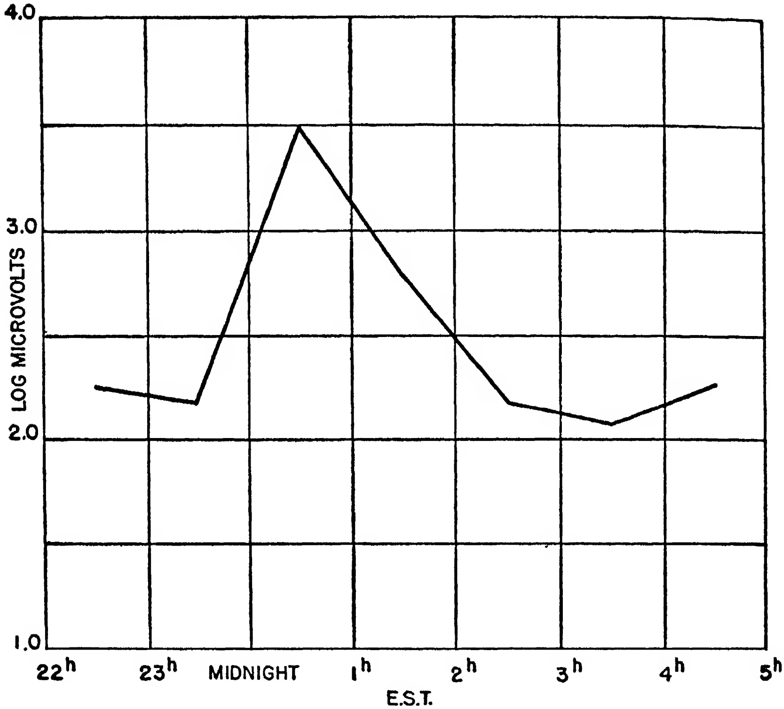


Figure 9. Sudden rise in critical frequency during the night of May 10-11, 1945, attributable to sporadic E

of the field received from the Washington station which lasts for two or three hours. Such a burst of signal strength in the middle of the night is attributed to an occurrence of this thing called sporadic E. What may be the cosmic cause of such bursts we do not know. There has been some indication that, in general, more sporadic E's are observed during the years of sunspot

maxima than during the years of sunspot minima. However, records of sporadic E have probably not been sufficiently extensive to determine just what relations these abnormalities may have to changes in solar radiation that follow the sunspot curve.

All of these problems emphasize the importance of the investigation of sunspots and their recurrences. Obviously, to know how to predict, well in advance, how much help or hindrance the sun may have to offer for radio communications over different paths and at different frequencies, we need to anticipate the number of sunspots that may be expected in the future. The problem of predicting sunspots is the subject of the contents of another chapter.

It will be observed that thus far the discussion relative to sunspots and radio reception has been concerned with sky waves of radio reflected from ionospheric levels. We have no reason yet for believing that sunspots or other solar activity materially affect the ground waves which are received from within fifty to one hundred miles of the broadcasting station. There is another type of radio propagation, however, in which the sun indirectly plays a part.

Very high and ultra-high frequencies waves travel in the lower atmosphere, and inasmuch as these frequencies are above the critical frequencies of both the E and F layers, we should not ordinarily expect that they could ever be returned to earth by the amount of ionization known to exist in the upper layers of the atmosphere. Waves of these high frequencies passing through the ionosphere penetrate it and are lost in space.

It was originally thought when the very high frequencies were discovered that they behaved much as light waves and could not be transmitted any great distances on account of the curvature of the earth. Anyone who indulges in the sport of yachting, or has taken ocean voyages offshore, knows that the visibility of a lighthouse depends upon the height of the tower

and the distance the ship may be off. A lighthouse, to be visible at a range of ten miles, must have its lantern one hundred feet above sea level in order to be seen in a rowboat on the surface of the ocean ten miles away. Beyond that range, the curvature of the earth will obstruct the light beam. Of course, if one is observing from the bridge of an ocean liner, perhaps thirty-six feet from the water's edge, this elevated bridge will make it possible to see the lighthouse farther and actually add another six miles to its range, so that a light one hundred feet above sea level can actually be observed by a navigator (whose eye is thirty-six feet above sea level) at a distance of sixteen miles.

Experiments with high-frequency radio waves soon showed that they could be received at distances far exceeding the optical range. One, therefore, had to revise one's theory to fit the observations. Every navigator knows that before using his sextant observation for determining the position of the ship he must correct the observed altitude of the sun for a certain bending of the sun's rays by the atmosphere. This phenomenon of the bending of light waves passing through the air is known as atmospheric refraction. Refraction, or the bending of light waves, may vary decidedly, and depends upon conditions of the atmosphere. Frequently an island beyond the horizon may actually be lifted into visibility through unusual temperature changes over the surface of the water. Lighthouses may occasionally be seen beyond the theoretical limit. It was natural, therefore, that radio engineers came to look upon refraction as the probable cause of the bending of the very short or high-frequency waves of radio. Considerable investigation has been accomplished of late in relating the vagaries of this high-frequency reception to the meteorological conditions which can change appreciably the amount of atmospheric refraction.

For well over a year radio waves from station W2XMN located at Alpine, New Jersey, and broadcasting on a frequency

of 42.8 megacycles, have been recorded at the Cosmic Terrestrial Research Laboratory at Needham, Massachusetts, a distance of 167 miles. Making allowance for the height of the antenna above the earth, the optical path for the range of this station would not be over twenty miles. If this line of sight from Alpine's antenna tangent to the earth at this point were extended into space, it would encounter the atmosphere nearly eight miles above Needham (Figure 10). Yet we know the wave is re-

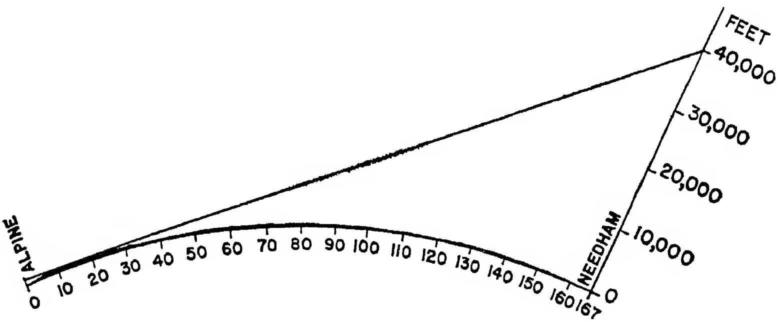


Figure 10. Profile of tropospheric path from Alpine, New Jersey, to Needham, Massachusetts, distance 167 miles, vertical scale multiplied ten times

ceived at Needham and therefore reason that the electric waves of radio, like the electromagnetic waves of light, must have been bent down by refraction in passing through the earth's atmosphere. In so doing, they reach the antenna of our receiving set, 167 miles distant from Alpine.

After a year of observation it has become very evident that reception is much better in the summertime than in the wintertime. Calculation shows that on account of the temperature and water-vapor content of summer air, as compared with winter air, these electrical waves would be bent towards the earth much farther in the warm season than during the cold season. The graph shown in Figure 11 shows the variation in the

strength of Alpine's radio waves as received at Needham from February, 1945, through January 1946. The upper curve in Figure 11 shows the calculated atmospheric refraction during the same interval. The close correspondence of these two curves leaves little doubt that the intensity of Alpine's field received at Needham follows the general law of the seasonal change in refraction. It will be observed, however, that the reception in

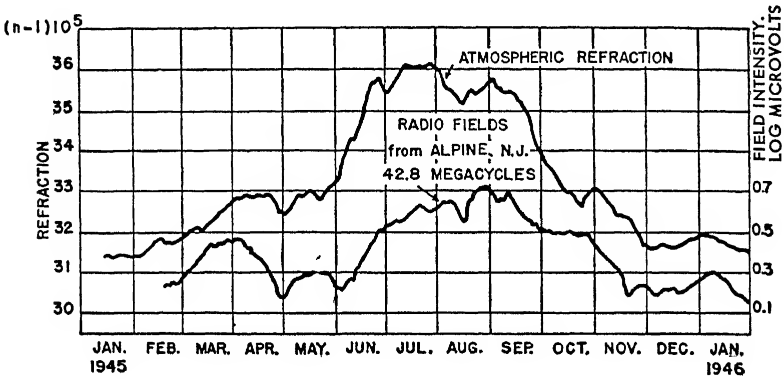


Figure 11. Variation in field intensity of FM station W2XMN, Alpine, New Jersey, 42.8 megacycles, as received at Needham, Massachusetts. Upper curve shows corresponding variations in atmospheric refraction

the spring of 1946 is definitely lower than during the spring of 1945. We had many more sunspots in the first half of 1946 than we had in the first half of 1945. We see no good reason, however, for believing that sunspots which can play such havoc with the ionization of the upper atmosphere should affect the atmosphere within the first few miles of the earth's surface. It does not appear probable from our present knowledge that sunspot activity is useful in predicting the vagaries of this very high frequency transmission that involves only the first few miles of the earth's atmosphere.

Meteorologists call this lower region of the earth's atmosphere the troposphere. It extends from the earth's surface up

to the stratosphere. Radio engineers accordingly refer to the kind of radio reception that is confined to the lowest layers of the earth's atmosphere as tropospheric reception. Some have conjectured that through the production of the larger amount of sporadic E ionization accompanying sunspots, radio waves in the forty to fifty megacycle band will be reflected from these ionospheric clouds responsible for sporadic E and thus cause serious interference with FM broadcasting. Until recently, FM, or frequency modulation, broadcasting occupied the band from 40 mc. to 50 mc. in the radio spectrum. We do know that in some unaccountable way police calls using these frequencies in distant cities have interfered with local police communications hundreds and sometimes thousands of miles away. We have no adequate reason, however, for believing at present that such phenomena can be attributed to sunspots. In fact, it has yet to be proved that sporadic E occurrences are intimately correlated with sunspot activity. Unless there is some kind of radiation from the sun accompanying the outbreak of sunspots which penetrates through to the earth's surface, seriously changing the ionization in the lowest layers of the atmosphere, we could hardly expect that sunspots would be an important factor in tropospheric reception such as is used in FM broadcasting and in transmitting television.[1]

Until we have a longer series of measured field intensities of these very high frequency waves, we shall content ourselves with recognizing refraction of the atmosphere as the principal cosmic factor in the vagaries of tropospheric radio reception. A very important factor, however, in this refraction is the water-vapor content of the lower atmosphere, and this has already been shown as a primary cause for better distant reception in summer than in winter in the forty to fifty megacycle

[1] This statement does not preclude the possibility of reception in the 40-50 mc band by oblique reflection from a heavily ionized E layer where the distance involved results in a very low angle of arrival of the waves.

band. Our observations indicate that the higher the frequency in this high-frequency range, the poorer the reception at stations beyond the optical horizon. From the point of view of the broadcaster, greater coverage may be anticipated at forty to fifty megacycles than in the region of eighty-eight to one hundred and six megacycles, the region to which the Federal Communications Commission has recently assigned FM or Frequency Modulation broadcasting.

There is a possibility that in the development of ultra-high frequencies greater stability for communications may be maintained through tropospheric reception than by using lower frequencies reflected from the ionosphere for distant communication. To avoid the complication of variable refraction, however, relay stations would probably have to be established at intervals not exceeding fifty miles. By means of reflectors, a concentrated beam of radio waves can be sent from one station to another, utilizing only transmission through the lower atmosphere. This dodges the difficulty of sunspots and the changing ionization accompanying them that is so bothersome in ionospheric transmission. The cost of such equipment, however, would be large, and it does not seem likely that these high-frequency tropospheric waves will replace ionospheric transmission very generally for some time to come. Such a method of relay stations, however, may be very useful in establishing telephone and communication lines over territories where cables and wires have not yet been strung, and we may rest assured that communication engineers are all ready to take advantage of any saving that such a relay system can afford as it becomes economically feasible to do so.

Chapter 6

SUNSPOTS, THE EARTH'S MAGNETISM, AND THE NORTHERN LIGHTS

EVERYONE KNOWS in a general way that the earth has a magnetic field, and that for this reason compasses can be used to find directions. Probably, likewise, most people know that the North Magnetic Pole is not the same as the north geographical pole, and that compass needles do not point to true north. There has been some debate recently as to the exact location of the North Magnetic Pole, for the results of the recent flight of a British plane on a scientific expedition to the north gave indications that the North Magnetic Pole had shifted by a hundred miles or more from where it was supposed to be located. However, the location of the North Magnetic Pole can be considered from latest observations as being north of Hudson Bay at approximately 73 degrees north latitude and 93 degrees west longitude. This places the North Magnetic Pole, some 1,100 miles south from the position of the true North Pole (Figure 12). Compass needles which point to magnetic north, therefore, will not be pointing true north unless the observer is on a meridian which passes approximately through both of these poles. Along a line from New Orleans to the western end of Lake Superior, the compass needle points very nearly true north because along this meridian in the United States the direction of the North Magnetic Pole is practically the same as the direction of the true geographic pole about which the earth spins on its axis.

A yachtsman sailing off the New England coast will find that his compass is pointing about 15 degrees west of north,

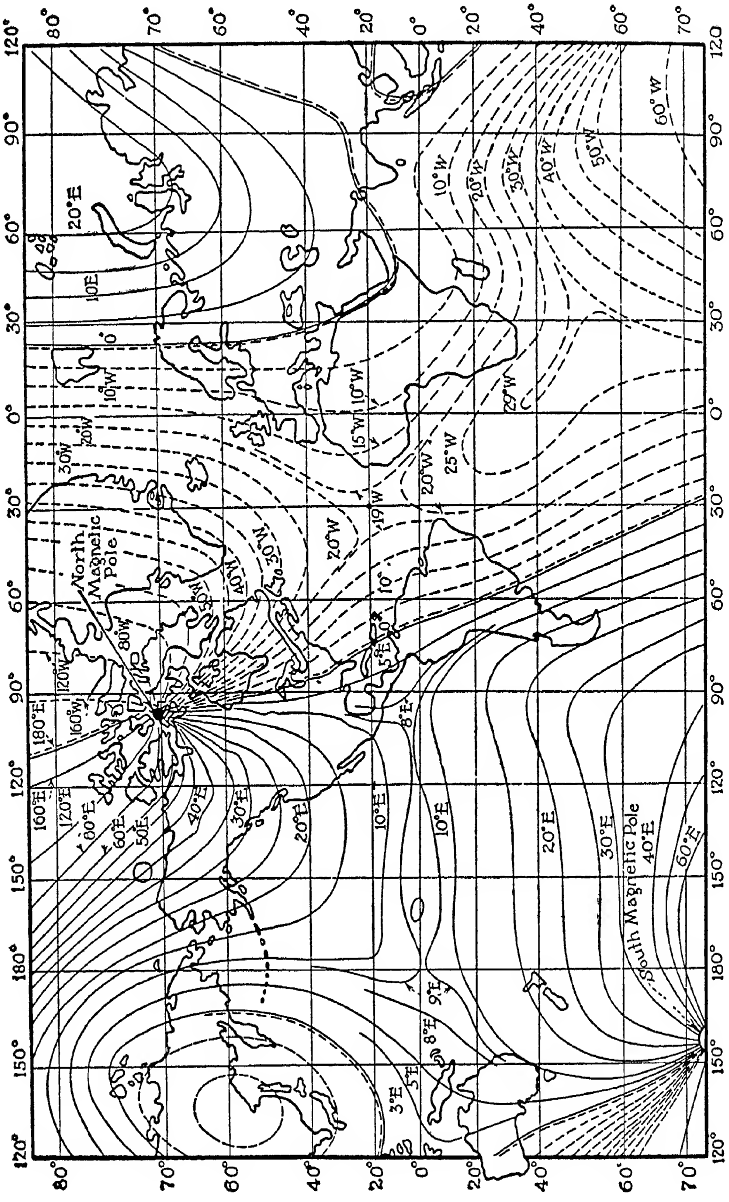


Figure 12. Map of the world, showing location of the North Magnetic Pole and isogonic lines representing compass variation

whereas at nearly the same latitude in Puget Sound, on the west coast, a mariner will find his compass pointing some 20 degrees east of true north. When you embark on your transatlantic trip to Europe, you leave New York with the compass pointing 10 degrees west of north. By the time you are off the Grand Banks, it is pointing nearly 30 degrees west of north. When you dock at Bremen, it is back at 10 degrees west again—the same as it was at New York.

To add to the complications, this variation of the compass is not the same this year as it was last year. It is constantly changing. Magnetic observations are made from time to time by the governments of the world and by scientific institutions for checking up on this temperamental field of the earth.

When the good ship *Half Moon* sailed into the mouth of the Hudson River while Manhattan was still held by the Indians, the compass was pointing north by west just as it does today. But by 1833 the compass could be relied upon to give true north to the entering ships as accurately as the polar star.

In France, in 1580, the compass pointed north by east. In 1666 it was pointing true north. During the War of 1812 the needle was pointing north-northwest. Since 1814 the needle has been swinging back, and today it is pointing only about 7 degrees west of the true meridian. Just what makes these mysterious changes in the earth's magnetism, science has not yet been able to find out.

In magnetic observatories stationed in selected regions of the globe that are remote from electric trains and power lines, it is found that the compass needle is continually wandering back and forth every day by a slight amount. As the sun rises in the east, the north end of the compass turns slightly in that direction. By noon, when the sun is due south, it is pointing in its normal position. Shortly after noon it begins wandering toward the west, following the sun as it goes down. By mid-

night, when the sun is below the northern horizon, it is back to normal again. This goes on day after day, month after month; but during the years when sunspots are most numerous, the excursions of the needle, on the average, will be twice as great as they are when sunspots are lacking.

Please don't think that these daily wanderings of the needle are of sufficient amount to lead you astray. In general they are not sufficient to be observed by the steersman of a trans-atlantic liner, but they are large enough to be observed by scientists and to cause no end of speculation as to the true explanation of this phenomenon.

The source, or the exact nature, of the earth's magnetism is still one of the great mysteries of science. We have as yet no good explanation for the long-term drift in the direction of the compass needle. Whoever first discovered the earth's magnetism is probably anybody's guess, and it seems probable that the idea of the compass came from some ingenious Oriental mind and found its way to Europe during the Crusades. Fortunately, magnetic observatories have been recording the behavior of the compass needle for well over a hundred years, and we know that sunspots have a way of upsetting the earth's magnetism. In fact, the close correlation of changes in the earth's magnetism with the coming and going of sunspots is one of the best established connections between sunspots and the earth that science knows. If we make a chart of the variations in the earth's magnetic force and the variations of sunspots, as is shown in Figure 13, we are impressed by how closely these two phenomena do correspond.

In interpreting terrestrial magnetism, it appears necessary to consider two sources upon which the earth's magnetism must depend. One of these sources lies deep in the interior structure of the earth, where presumably a nickel-iron core retains a more or less permanent magnetic set, like that of a steel bar magnet. The other source of the earth's magnetism, and probably the

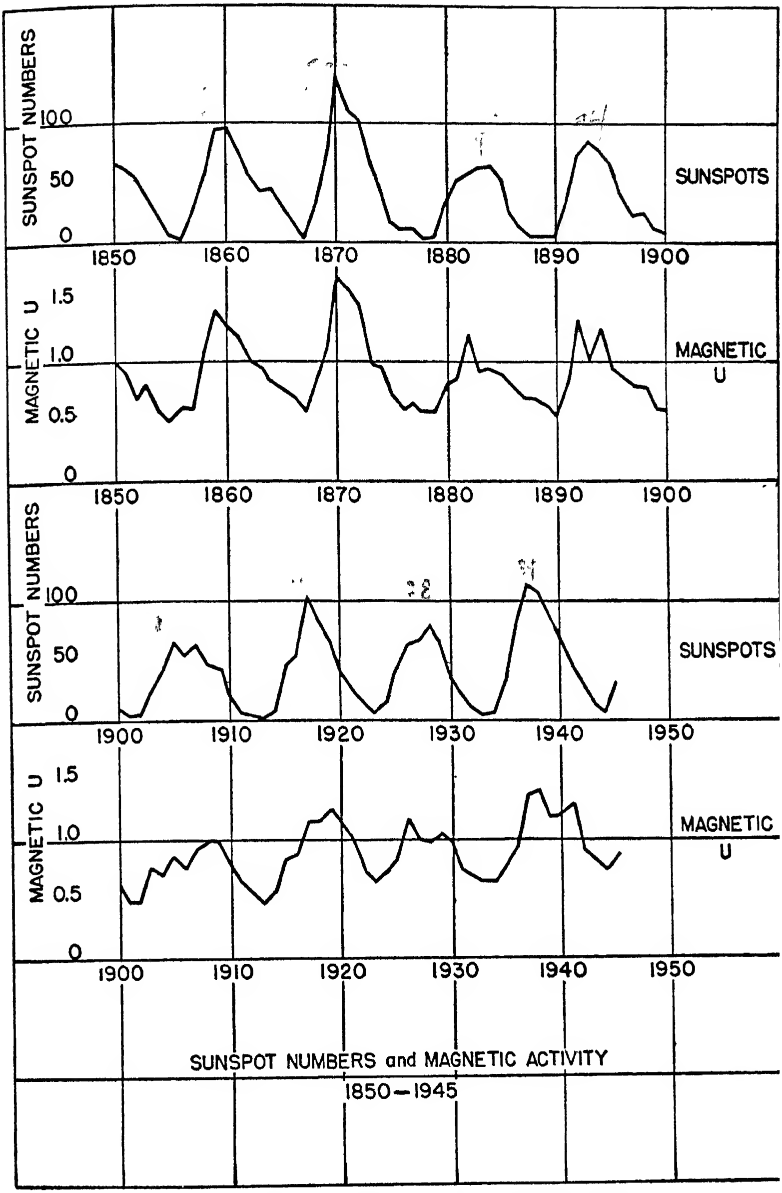


Figure 13. Sunspot numbers and magnetic activity

source which is most easily disturbed by outside influence, is to be found in the upper layers of the earth's atmosphere. These upper layers, being ionized by radiation from the sun, become conductors of electricity. As the ionized particles in the atmosphere circulate about the earth's axis, owing to the earth's diurnal rotation, the moving ions constitute an electric circuit circulating about the axis of rotation.

From the elementary laws of electricity a current traveling in a circular wire loop induces a magnetic field within the loop. The effective intensity of this field may be very greatly augmented by the insertion of an iron bar perpendicular to the plane of the loop. Thus we see that the circulating electrical currents caused by the rotation of the ions in the earth's atmosphere will, by induction, tend to alter the magnetism in the iron core of the earth; and every change in the electron density of the upper atmosphere will be accompanied by changes in the intensity of the earth's magnetism. Solar disturbances, cosmic rays, and any other source of ionization of the earth's atmosphere may therefore be expected to leave their mark in disturbing the delicate magnetic needles which have been set up for observing fluctuations of the earth's magnetic field.

With the advent of radio and the discovery of the ionized layers of the atmosphere, one can see how the mysterious connection between sunspot activity and changes in the earth's magnetism can be linked together.

When an unusually large group of sunspots is observed, we may expect not only a sudden disturbance in radio reception but also a simultaneous disturbance in the earth's magnetic field, and we are in position now to see that the principal cause of such mysterious magnetic changes lies in the sun itself. In the early days of wireless it was found by some observers that while communication conditions were poorer on certain wave lengths, they often were better on other wave lengths following such magnetic disturbances, often referred to as magnetic storms.

We can understand how such conflicting results would be confusing to the radio engineers of yesterday. Today, when we understand better how the transmission of radio waves of different frequencies depends upon the degree of ionization of the atmosphere, we are less confused by such apparently discordant reports. Communication paths and wave lengths which need a high state of ionization may be improved when the increase of ionization accompanying a magnetic storm takes place. Frequencies and communication paths which operate more efficiently with a lower state of ionization will under similar circumstances be seriously disrupted.

It should be emphasized that the magnetic storms to which reference is made in this chapter have nothing to do with thunderstorms, but have only to do with disturbances in the magnetic field of the earth which to the ordinary observer pass unnoticed. It is, however, when such disturbances attain a sufficient magnitude to interfere with radio communication and to induce electrical interference in telephone and power lines that the characteristic headlines find their way into front-page news.

To the ordinary observer, there is, however, an outstanding phenomenon that frequently accompanies huge sunspots and magnetic storms that is sure to command attention. This is a display of the aurora or northern lights. These conspicuous phenomena give assurance of electrical discharges taking place in the high atmosphere due to the heavy ionization of the upper air associated with sunspots.

When a huge group of sunspots breaks out on the surface of the sun, a stream of electrified particles reaching the earth can so heavily ionize the upper layers of the air as to interfere not only with radio sky waves but also to create sufficiently high electrical voltages as to cause visible discharges in the very rarefied air, causing it to glow like the glow in the neon signs that illuminate Broadway. Dr. Carl Störmer, a famous Nor-

wegian scientist, has for many years photographed and studied auroral streamers and has found that they may attain heights from four hundred to six hundred miles above the surface of the earth, thus indicating that the thin air must extend to that height.

If we imagine a glass tube from which air can be exhausted by an air pump, we can easily simulate conditions that would be encountered were we to ascend to these high levels. To apply such electrical potentials to the ends of this tube as would appear to exist aloft, we need two short wires or electrodes entering the glass tube at either end as a means for providing high voltage across the terminals. Before starting the air pump to evacuate the tube, we shall find that under ordinary atmospheric conditions no electricity will pass or any discharge take place within the tube at such voltages as we may have available. Air at ordinary conditions is a relatively poor conductor of electricity. If, however, we start a vacuum pump and begin to exhaust the air from the closed tube, the pressure will be reduced and in time we shall see that an electric current begins to pass through the rarefied air from one end of the tube to another, causing a diffuse glow within the whole tube. Soon the color of this discharge will begin to simulate the red tints of the aurora. As the vacuum in the tube increases, we can imagine ourselves rising higher and higher through the stratosphere. The red glow will gradually give place to a pale-blue color. This occurs as the ionization of the thinning air in the tube becomes more complete. Under these conditions, the molecules of the air within the tube are becoming scarce and simulate conditions to be found at the top of the atmosphere four hundred or five hundred miles high. If we completely exhaust the air, the current will again fail to pass, and we have obtained conditions of vacuum below the limit of atmospheric density necessary for an auroral glow. This is an illustration of the way in which the northern lights are formed in the upper atmosphere of the

earth under the electrical excitation caused by the bombardment of streams of corpuscles emitted from the sun in the vicinity of sunspots.

Almost every auroral occurrence is accompanied by violent disturbances of the earth's magnetism, causing a typical magnetic storm in which compass needles oscillate and wander. Communication conditions for radio are simultaneously disturbed, if not completely blacked out. If the aurora is an unusually bright one, these magnetic disturbances may be accompanied by heavy electrical currents induced in the earth and in wire and cable lines carrying telephone and telegraph messages, often causing serious distortion of the message intended.

One of the more brilliant auroras during the last sunspot maximum occurred on Easter Sunday, March 24, 1940, and seriously wrecked many affectionate Easter greeting telegrams. One such message came through on the multiplex teletype as follows:

> "GOVE AND EAETER GREETINGS FROM AGLWGRACZ MGOPBWQQTPOZLQPVPMGXPZGXHVWYQPMRQPWVV ZPVW"/°/WXQQVVWVPVMOZQOQQQWQWVWQMVN."

One surmises that there was an endeavor to send love and Easter greetings, but any correspondence between the name and address of the sender and what followed the message must be regarded as purely accidental. What happened was that stray currents induced in the telegraphic wires took over the control of the type bars, thus proving that sunspots can seriously interfere with world affairs.

It will be interesting to note the effect on our field-strength measurements of the broadcast station WBBM, Chicago (780 kilocycles), for the two weeks around the date of this Easter disturbance in 1940. The average normal reception for an evening may be assumed to be about 100 microvolts. It will be noted that we had abnormally high reception for the week pre-

ceding the aurora, the highest field of these nights being observed six days before it. Figure 14 depicts the field strength in microvolts as received each day from March 17th to April 2nd. These medium-frequency radio waves presuppose reflection from the lower or E layer of the ionosphere. It will be noted that there was a forewarning of the aurora on the night of March 23rd, when WBBM's field fell below 50 micro-

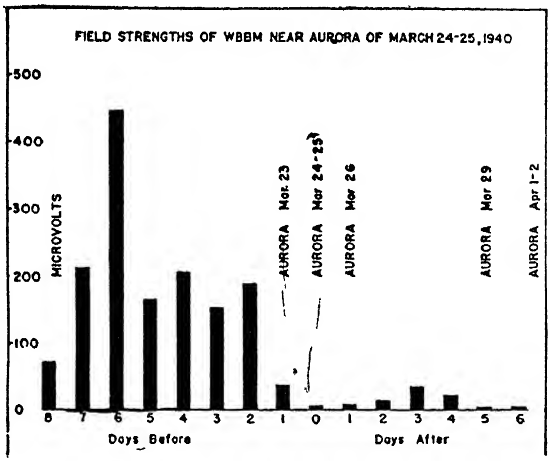


Figure 14. Field strengths of WBBM near aurora of March 24-25, 1940

volts. On the night of the aurora, and for two days following, reception was barely recordable. It tried to recover on March 28th and 29th, but additional auroras followed which again killed reception, and more than a week elapsed before there was anything like normal recovery of reception over this path.

Another conspicuous aurora occurred on the evening of September 18, 1941, and Figure 15 shows the resultant measurements of field intensities on both WBBM (780 kilocycles) by way of the E layer, and on WWV, Beltsville, Maryland, (5,000 kilocycles). Again it will be seen that in general reception was good for the week preceding the aurora, and that the

fields were practically zero on the night of the aurora. It should be noted that the recovery on the 5,000-kilocycle frequency was more rapid and complete than on the 780-kilocycle frequency which remained low for a week following the aurora.

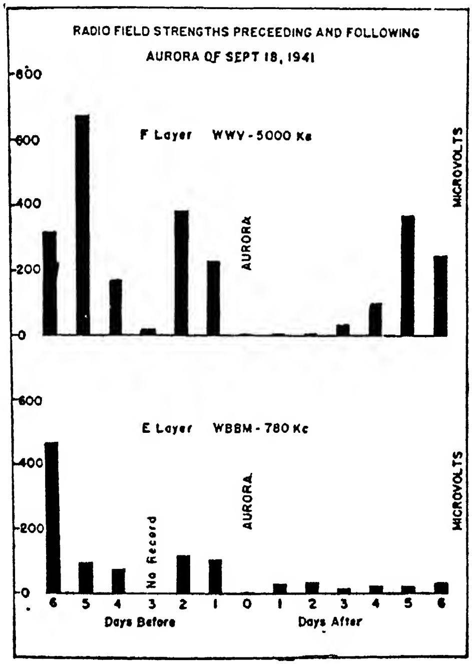


Figure 15. Radio field strengths preceding and following aurora of September 18, 1941

An analysis of ten years' observations of auroral and radio phenomena shows even more clearly the relation between the time of maximum solar activity, auroral occurrences, magnetic disturbances, and disturbances in the E and F layers of the ionosphere. In the graph of Figure 16 the top line of columns represents the relative sunspot numbers from six days before to six days after the time of auroral occurrences, designated by zero. It is seen here that the fewest number of sunspots occur

four days before the date of an auroral occurrence, but that there has been a marked increase of sunspot activity up to the day preceding the aurora. After the auroral occurrence, solar

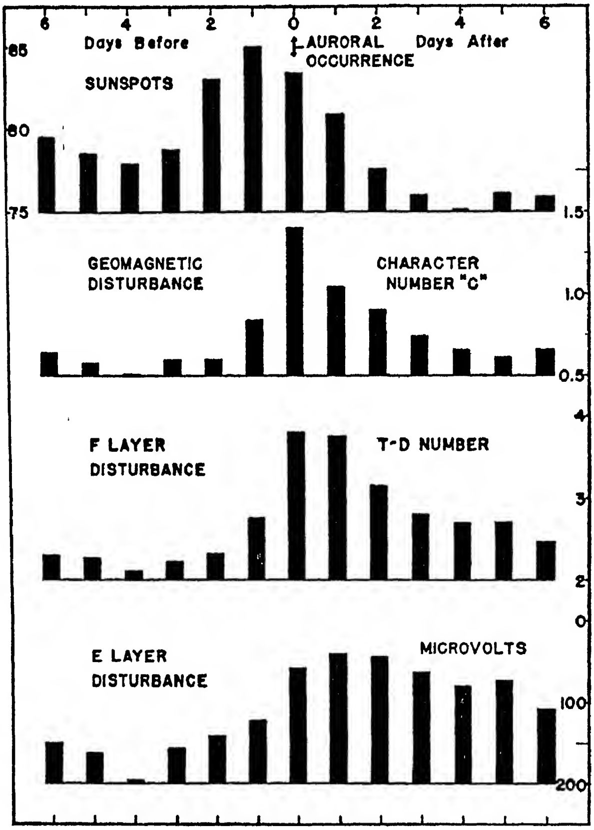


Figure 16. Sunspot disturbances, geomagnetic, F-layer, and E-layer disturbances, following the sequence around auroral dates

activity is shown to diminish. This can be attributed to the fact that the group of sunspots causing the aurora has been carried across the sun's surface by its rotation, and presumably also has in the meantime diminished in intensity. In the second

line of columns there are represented the degrees of geomagnetic disturbances in the same order of days. The index here plotted is technically known as the character number "C", a numerical value compiled at various magnetic observatories. The value zero for characteristic "C" has been adopted for an undisturbed day, and a value of 1.5 to 2.0 indicates very disturbed days. The study of this graph shows the least magnetic disturbances on the earth to have occurred four days before the occurrence of an aurora corresponding to the lowest value in the sunspot numbers. With the occurrence of the aurora on "zero day," the magnetic-disturbance figure rose to its maximum height, gradually subsiding in the five days following.

In the next line of columns, the disturbances are plotted for the F layer of the ionosphere obtained from observing short-wave reception across the Atlantic. We see here that the fourth day before the occurrence of the aurora was the day of least disturbance, and that the day of the aurora and the day immediately following showed the greatest disturbance in the F layer.

Finally, the lowest row of columns in Figure 16 represents the disturbances to the lower E layer of the ionosphere from which the 780-kilocycle waves from Chicago's broadcasting station, WBBM, are transmitted. Once more we see the least disturbed day was four days before the aurora, and that the E layer was more and more disturbed until the maximum degree of disturbance occurred on the day following the aurora and the day immediately following that. It will also be noted that the decrease in the disturbances in the E layer was much more slowly accomplished than in any of the upper graphs.

We might infer from the studies of the above graphs that about a day elapses from the time of maximum disturbance on the sun until the top of the earth's atmosphere is sufficiently ionized to produce the visible glow of the northern lights. When

the ionization has attained this degree, the magnetism of the earth has attained its maximum disturbance, and the F layer has become so disrupted as to produce violent disturbances in radio short-wave communication, the type of communication that depends upon reflection from the F layer one hundred and fifty miles high. It is to be noted that another day elapses before the disturbances due to this ionization have created the greatest effect on the E layer from which radio waves in the

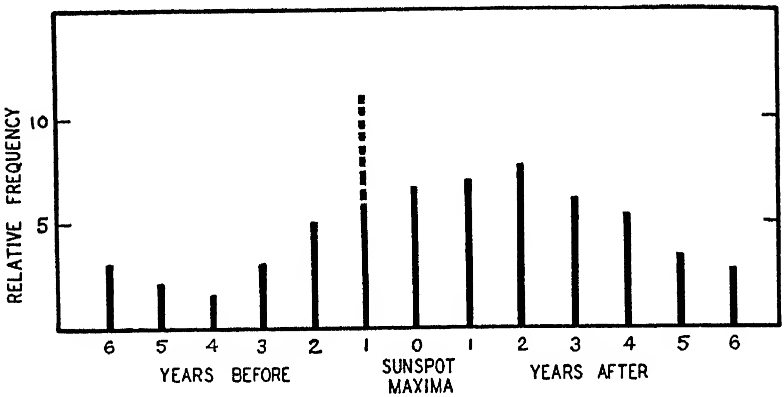


Figure 17. Auroral occurrences from six years before to six years after years of sunspot maxima

broadcast band are reflected, seventy miles above the earth. Another important deduction is that the disturbance once felt in the E layer persists for a much longer time than the disturbance caused in the F layer.

If we make a chart of the numbers and occurrences of auroras, we find that there seems to be a close connection between the frequency and brightness of auroral displays and the state of the sun as it is marked by sunspots. Utilizing thirty years' records of auroral observations from the Blue Hill Observatory, we have in Figure 17 a graph showing the number of auroral occurrences per year from six years before

to six years following maxima in sunspots. The fewest number of auroras appear to occur about four years before sunspot maxima, and the largest number of auroras are found to be in the second year after sunspot maxima have occurred.

The fact that auroras appear to occur with greater frequency two years after sunspot maximum rather than at the year of sunspot maximum itself may at first seem somewhat puzzling. There is, however, I believe, a plausible explanation for such a fact. As sunspots begin to wane after the year of maximum, they are invariably occurring in regions on the sun progressively nearer the solar equator, and for this reason will more nearly pass in line with the earth as they are carried across the disk by solar rotation. We have good reasons for believing that sunspots more nearly in line with the earth are more effective in producing terrestrial effects than those occurring on regions on the sun remote from the equator. Thus, while sunspots may actually be smaller in size and less frequent in number after the year of sunspot maximum, they may be more effective in pouring streams of electrified particles into the upper atmosphere, producing the principal cause for the appearance of the auroras or northern lights. During the subsequent years, the spots are favorably situated for such emitted streams of particles to reach the earth, but they are then so rapidly diminishing in size and in number as to statistically cause fewer and less bright auroras. Hence the falling-off in frequency of auroras from two to five years after the sunspot maximum.

Recently, Dr. Carl Störmer, from the study of thirty-two thousand auroral photographs, was able to determine the heights of more than twelve thousand auroral streamers occurring since 1911. By far the greatest number of auroras occur between 90 and 120 kilometers above the earth. On three occasions auroral streamers reached the extreme height of 1,000 to 1,100 kilometers. The frequency of such occurrences is

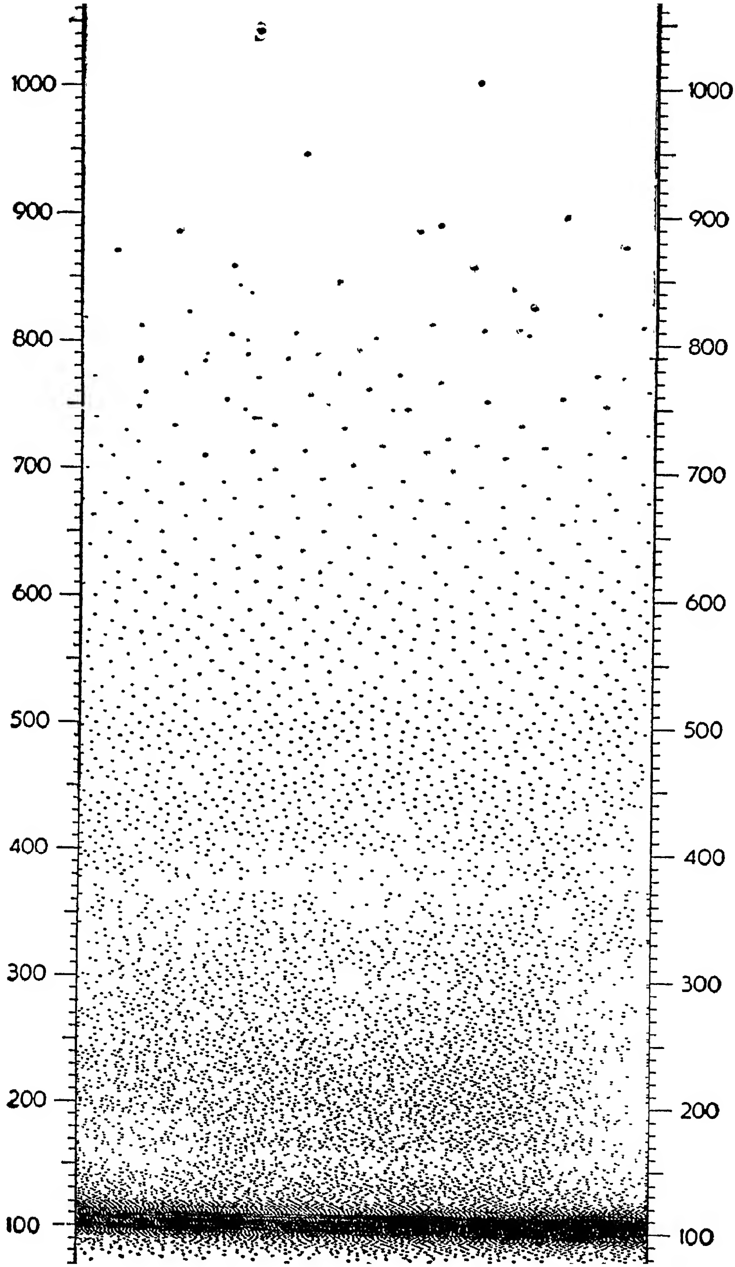


Figure 18. The vertical distribution of auroras

illustrated in the vertical distribution of the dots shown in Figure 18.

A remarkable auroral display occurred on February 7, 1946, accompanying the appearance of the largest sunspot group on record. It was attended by one of the most extensive disturbances to radio communication of the present sunspot cycle.

Chapter 7

RADIO AND THE MOON

WHILE IT IS generally accepted that the sun is chiefly responsible for the ionization of the earth's atmosphere, which makes radio transmission possible, we can readily appreciate that any cosmic factor that adds to or diminishes the state of ionization, or changes the distribution of the ions in the upper atmosphere, must have its effect upon the transmission of the electromagnetic waves of radio. Were we to summarize all of the known causes of the ionization of the upper atmosphere on the basis of the energy received from known sources, we should find values very much as follows, as they have been summarized by A. M. Skellett from reliable sources.

Sources of Ionization		Energy Received by the Earth: Ergs per Square Centimeter per Second
Ultraviolet light from the sun		28.35
Meteors during meteoric shower (A.M.) up to		2.4
Ultraviolet light from the stars (approximate)		0.014
Cosmic rays		0.00031
Meteors—average normal day:	A.M.	0.00024
	P.M.	0.00012
Ultraviolet light from the full moon		0.000044

All of these values may be subject to revision, since estimates have had to be based on certain fundamental assumptions. This list, however, shows us that by far the greatest amount of ionizing energy is in the ultraviolet light of the sun. Next in order may be an unusual display of meteors during a meteoric shower in the early morning hours when the velocities of meteors striking the earth's atmosphere are greatest. The ultraviolet light

from the stars, based on Eddington's figures, appears rather insignificant in comparison with solar radiation. Even the highly energetic cosmic rays appear to play a very small part, if the value taken from Millikan and Cameron's estimate is correct. At the bottom of the list comes the light from the full moon, which even in the visible region of the spectrum is only 1/300,000 as bright as sunshine. Certainly one could not expect ordinary moonlight to add any significant amount of ionization to the upper atmosphere on such an assumption.

There are other ways, however, in which the moon may change the distribution of ions and electrons in the upper atmosphere.

For many years it has been known that the moon has a small magnetic effect on the compass needle. This could be produced were the moon a magnetized sphere like the earth, or were it to create tides in the ionosphere, thus changing the distribution of ions and creating small electrical currents in the upper air which by induction would impose periodic changes in the magnetism of the earth as the moon revolves about it.

Students of geomagnetism are quite familiar with certain periodic changes in the earth's magnetism that follow the motion of the moon about the earth. An analysis of these changes indicates that these variations are not entirely explained on the supposition that the moon itself is a simple magnet. If, on the other hand, the moon, through some means, changes the distribution of ions in the upper atmosphere, we should anticipate an effect on the earth's magnetism and should have good reason for expecting some systematic variation in long-distance radio reception that correlates with the moon's position in the sky.

Some years ago we made an analysis of our extensive records of the measured field intensities of the WBBM broadcasting station in Chicago (770 kilocycles) to see if there were any evidence of such an effect that would be appreciable enough to produce any change in radio reception that could be attributed

to the moon. As far back as 1931 we did find evidence of some effect of the moon on the ionosphere that introduced a periodic change in radio reception depending upon the position of the moon. An actual rise and fall in barometric pressure accompanying the moon as it revolves about the earth has been found by meteorologists. The question arose as to whether or not this rise and fall of the atmosphere produced by the gravitational attraction of the ocean of air was the true explanation of the change we measured in radio during the passing of the moon across the sky. The change in the barometric pressure produced by the lunar tidal wave in the earth's atmosphere is only about 1/200 of a millimeter of mercury at the earth's surface. The change in the radio field intensities which we observed, that appeared to correlate with the moon, sometimes appeared to be as much as 40 per cent of the normal field strength. From the change in barometric pressure at the earth's surface, however, it is not easy to arrive at a definite conclusion as to just how much the ionized layer may rise and fall by the gravitational action of the moon on the upper atmosphere. It may be possible that even a small change in the distribution of ions can make a very large change in the intensity of the field of the radio wave received over a considerable distance. Some time later (1934) E. V. Appleton, a distinguished English scientist and radio engineer, came to the conclusion that with the passing of the moon about the earth there was a semi-diurnal variation of one whole kilometer in the height of the ionosphere. Appleton's results were based upon ionospheric soundings over a considerable period. He came to the conclusion that his observations indicated an ionospheric tide at the level of the E layer nearly six thousand times as great in magnitude as that indicated from the barometric pressure changes observed at the earth's surface.

Some time after our early publications concerning the correlation of radio-field strengths with the position of the moon, I began to receive communications from engineers and radio

men in different parts of the world calling attention to the fact that they often observed great differences in world-wide communication conditions at full moon as compared with new moon, or when the moon was at either first or last quarter. In 1937, Jörgen Hals of Bygdöy, Norway, called my attention to several years' observations that he had compiled, in which he had observed a drop in the signal strength of reception after each quarter of the moon. Investigation of the literature showed that as far back as 1913 the *London Electrician* had published articles on the relation of wireless reception to the phases of the moon.

The idea that feeble moonlight only 1/300,000 of the intensity of sunlight would have any effect on the ionization of the upper atmosphere seemed so improbable that I scarcely thought it worth the time and effort to make any special investigation. Had it not been that the subject had been forcibly brought to our attention, we should probably not have tackled the problem. We had at the laboratory in convenient form for analysis over eight years of observations of field-strength determinations of the waves received near Boston from the broadcast station in Chicago. It was thought that only a small amount of the available data that altogether comprised many thousands of hours of measurements would be necessary in order to show from our records that no significant change in radio reception occurred with the changing phases of the moon.

At the outset, using only a relatively small amount of the data, conveniently filed in a card catalogue, we sorted about 2,000 cards in the order of increasing radio field strength and compared these with the age of the moon which had been listed on each card for each night's observation. We then plotted our results. It was observed that the points scattered about rather widely, seeming to show no preference in their distribution with respect to the phases of the moon, or its age in days from new moon, as is commonly expressed. On closer study it appeared

that there was a slight indication of a rise in the curve shortly before full moon, or when the moon's age was eleven days after new. This suggested a more thorough investigation to remove all doubt. So it was decided to utilize all of the data from 1930 to 1939. In order to provide a check on any significant results, the data cards were divided into two groups of four years each, 1930-1934, 1935-1939. Obviously, the light of the moon could have an effect only when shining on the transmission path between Boston and Chicago. Certainly, moonlight could have no effect when the moon was below the horizon during the hours of our radio observations. Accordingly, each four years' data were divided into two parts; one part consisting of the observations made when it was known that the moon was above the horizon, and the other part comprising observations made on nights when it was known that the moon was below the horizon. Each of these four stock piles of card data was analyzed in turn.

The results were more than surprising. In place of the widely scattered points of observation found from our first test when we neglected to separate out the data made in the dark of the moon, we found now a reasonably smooth curve rising from relatively low field strengths a few days after new moon to relatively high field strengths occurring about two days before full moon. A subsequent fall thereafter was again followed by increasing field strengths until the moon had passed last quarter. This proved to be the case both in the 1930-1934 observations and in the observations made between 1935-1939. The change in the variation, however, was greater during the second four years than during the first four years. When we analyzed similarly the data observed on those nights when the moon was below the horizon, we found no such effect at all. Did this mean that moonlight was actually changing the field intensity of our Chicago station, depending upon the phase of the moon, as its light shone over the 900-mile transmission path between Chicago and Boston? In Figure 19 is shown the rise and fall of the

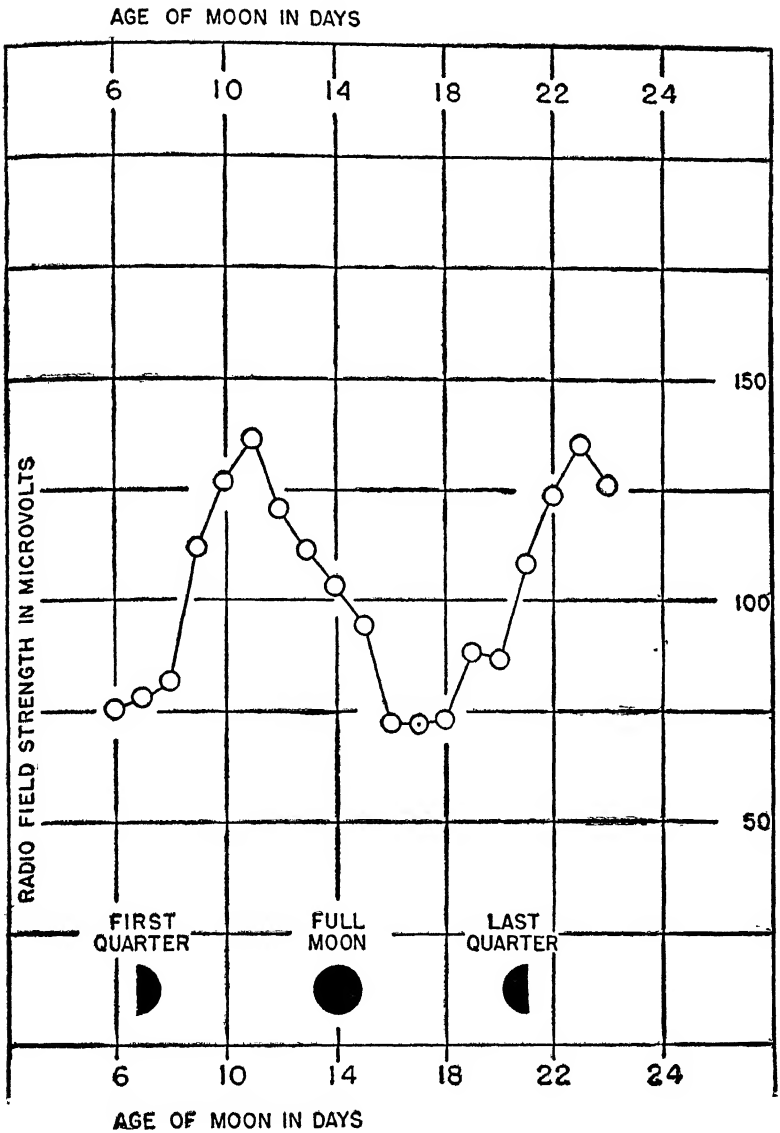


Figure 19. Observed variation in field strength in the broadcast band with the phases of the moon

measured fields in microvolts with the increasing "age" of the moon in days.

It is often one of the strange turns of fate in scientific research that one makes a certain hypothesis and in attempting to prove it from observation will, in the long run, find that the observations themselves may show the opposite of the hypothesis assumed. You see, our hypothesis was that moonlight could have no effect upon radio reception. If this had been correct, we should have expected no regular change of field strength with the change in the phase of the moon. Our observations indicated so conclusively that there was a systematic variation in the strength of the radio fields from Chicago with the phase change in the moon that, rather reluctantly, we came to the conclusion that if moonlight is not capable of producing such ionization as would cause the change in field intensities, then there must be some other explanation to account for a change in the ionization of the upper atmosphere, as the moon increases its elongation from the sun during the course of the month. Any explanation must also in some way explain why the lunar effect which we obtained appeared to be greater from 1935 to 1939 than during the years 1930 to 1934.

It is to be noted that the years 1930-1934 were years of low sunspot activity, whereas the years 1935-1939 were years of considerable sunspot activity, including the year of maximum sunspottedness in 1937. We know that sunspots have a very significant effect upon the ionization of the upper atmosphere and radio reception. Could it be that in some indirect way the radiation from the sun, striking the moon, could have its effect on the earth's atmosphere other than the effect of ordinary illumination? This reasoning led us to adopt another hypothesis which so far seems reasonably consistent with the facts of observation.

We know that there is a great deal of intense ultraviolet radiation emitted from the sun as dark light which we can-

not see. We have also increasingly good reasons for believing that X rays may be emitted from the sun. Experiments in the laboratory show that whenever a stream of X rays bombards the target, some of these X rays are reflected, and secondary X rays may be emitted from the target itself. Furthermore, even without invoking X rays, ultraviolet light shining on most substances frees electrons from those substances which it strikes. This is familiarly known as the photoelectric effect. It is this principle that is used in operating the photoelectric cells that open the doors in the Pennsylvania Railroad Station in New York City and in many other public buildings as you pass across the light beam.

We have, in space, the sun emitting intense ultraviolet light and possibly X rays which strike the naked surface of the moon as a target. The moon, unlike the earth, has no atmosphere to act as a protecting screen from these penetrating rays from the sun. When these high-energy solar rays, therefore, strike directly the materials on the surface of the moon, photoelectrons and possibly X rays will be emitted as invisible radiation. When such electrons or X rays, freed from the lunar surface, strike the earth's upper atmosphere, they will ionize the atmosphere very much as direct sunlight does, although to a very much less degree. The number of electrons liberated from the moon in the direction of the earth would depend upon the intensity of the ultraviolet sunlight falling upon the moon's surface, and upon how much of the illuminated surface of the moon is turned in the direction of the earth at a given time.

We see, on this hypothesis, how we could expect a greater contribution to the ionization of the earth's atmosphere from the moon during the years of sunspot maxima than during the years of sunspot minima, for it has long been recognized that the intensity of ultraviolet light from the sun during the sunspot maxima is from two to two and one-half times as great as during sunspot minima. This will explain the fact that such a

lunar effect as is produced on radio reception should be greater in the period from 1935 to 1939 than during the years 1930 to 1934 which included the sunspot minimum.

Good nighttime radio reception from Chicago depends upon a certain critical state of ionization in the E layer. There must be enough ions and electrons to reflect the waves well from the radio ceiling, yet too great an amount of ionization renders the lower atmosphere conducting and absorbs energy from the radio waves. We can see now how nighttime reception may be improved by the contribution which electrons from the moon may make in producing better reflection from the radio ceiling in the upper air. This ionization will increase with the increasing angle of elongation of the moon from the sun. As the moon passes through first quarter toward full moon, a larger area of the surface exposed to the sun sends more and more ionizing radiation toward the earth. If this ionization increases beyond a certain point, however, it will absorb some of the energy in the radio waves reflected from the E layer, and we can again expect a diminution in the field intensities measured. We see this absorption effect constantly illustrated in our twenty-four-hour field-strength recordings of WWV 5 megacycles from Washington, as was exhibited in Figure 3 (page 46). There, the heavy noontime ionization of the F layer caused a deep drop in the intensity of the field, as observed at Needham. We know, furthermore, that the lower-frequency waves, such as those of 770 kilocycles broadcast from the Chicago station, are much more sensitive to absorption than the higher-frequency waves of WWV.

On our present hypothesis, therefore, we see a reasonable explanation for the rise in field strength from the time of the moon's first quarter to shortly before full moon. The slump in the field intensity curve for a few days thereafter, with a subsequent rise again, may be explained as an absorption effect due to too many ions. When the rate of recombination of the ions

exceeds the rate of manufacture, absorption lessens and field strengths rise as the waning moon nears last quarter, twenty-two days after the last new moon.

In connection with our hypothesis, it was of interest to see what relationship, if any, might exist between the age of the moon and soundings of the ionosphere made by the usual method of determining critical frequencies. In determining critical frequencies by the method of receiving the reflected pulse back from the higher layers of the ionosphere, the apparatus will frequently show abnormal reflections from the E layer, due to increased ionization. Through the courtesy of Professor H. R. Mimno of Harvard University, we obtained ionospheric data covering the years 1933 and 1934 showing such reflections from the E layer in varying amounts. These ionospheric data were records of the reflection of pulses at normal incidence from a wave sent up at a frequency of 3,492.5 kilocycles. These waves under ordinary conditions of ionization would be expected to penetrate the E layer. The number of reflections received from the E layer, as compared with reflections from higher levels, made it possible to tabulate the percentage of reflection at E-layer heights.

The elongation of the moon from the sun was calculated corresponding to the days and hours for which the observational material was at hand. The relationship between the angle of elongation of the moon from the sun and the phases of the moon is a direct one. The elongation is zero at new moon, 90 degrees at first quarter, 180 degrees at full moon, and 270 degrees at last quarter. The upper curve in Figure 20 shows the distribution we found for E-layer reflections plotted against the elongation of the moon from the sun. Since it appeared that there was a seasonal variation in the data, we next corrected for this and obtained the lower curve in Figure 20, with due allowance made for seasonal changes. It will be noted that the percentage of reflection from the E layer in this instance

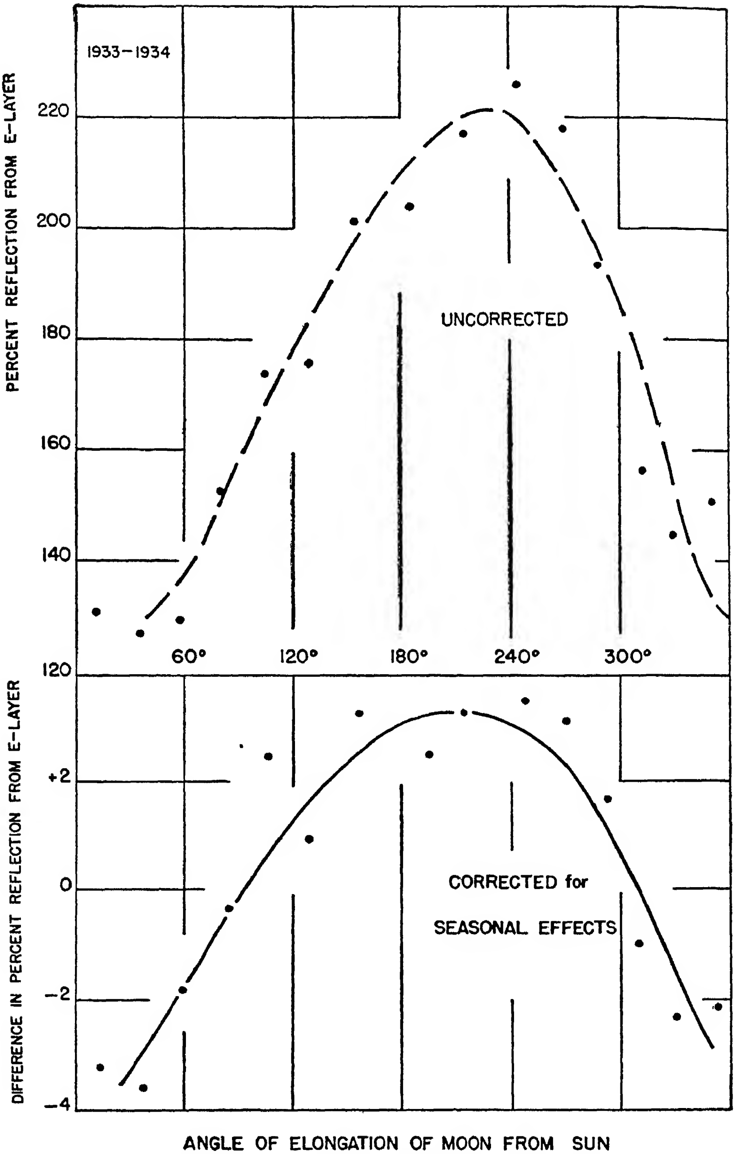


Figure 20. Percentage of normal reflection from E layer of 3.49 megacycles, as correlated with the phases of the moon

varies from -4 to a $+4$ from the normal value for this interval taken on our vertical scale as zero. It will be seen that the maximum value occurs when the angle of elongation between the moon and the sun is 250 degrees, corresponding to the moon's age of 14.2 days or approximately a little after full moon. This seems to indicate, quite independently of our field-strength studies, that a maximum effect of ionization from the moon occurs at this time and is consistent with our reasoning above. It will be remembered that the field intensity recorded at full moon (fourteen days old) was actually weaker then that at eleven days past new moon. This decrease we attributed to the absorption of the field by the stronger E-layer ionization accompanying full moon.

The problem of interpreting field intensity, we may emphasize, is somewhat complicated because it involves not only the question of sufficient ionization for good reflection of the radio waves, but also the effect of the absorption if too many ions are created in the lower atmosphere. The results of our studies of E reflections, however, during a part of the same period covering some of our field strength data, seem to be consistent with the interpretation made, if we assume that the secondary drop occurring at moon's age sixteen days is due to the absorption caused by more than the optimum ionization. Both lines of approach indicate that the greatest percentage of ionization occurs shortly after full moon.

It is also interesting to consider the possibility that a certain amount of atomic disintegration, or atom splitting, may be caused in the elements of the lunar surface while it is being exposed to the high energy radiation of the sun. We might use an analogy, and picture the sun as a gigantic cyclotron hurling ionizing radiation at the naked surface of the moon as a target. Since the moon turns very slowly on its axis, a given region of the moon's surface is exposed to such a bombardment from the sun continuously for two weeks at a time. After this in-

terval, due to the rotation of the moon on its axis, such a region would pass from the illuminated half of the moon into the dark half that presents itself to the earth following full moon. At last quarter, half the moon appears bright and half appears dark, as seen from the earth. Some of the elements on the moon may by this time have become artificially radioactive, just as specimens placed in the path of the beam emitted from a cyclotron are artificially made radioactive. Under these circumstances, then, a considerable area in the dark half of the moon near the sunset line, or the terminator, as astronomers call it, could be emitting radioactive products such as gamma rays. These in turn would make some contribution to the ionization of the earth's atmosphere when they reached the earth.

Of course the same intense radiation which strikes the moon's surface also reaches the earth from the sun, but the earth has an atmosphere to absorb most of this radiation in ionizing the upper atmosphere, thus forming the ionospheric layers. The moon, having no atmosphere, has no such defense shield. The ionizing radiation of the sun must strike the atoms of the elements of which the moon's surface itself is composed with their full energy. The length of time that such artificial radioactivity may be effective in coming from the moon will depend upon the half life of the elements that go to make up the surface of the moon. This might vary from minutes or hours to days, dependent upon the characteristics of the elements made temporarily radioactive.

One difficulty in thinking of electrons, or negatively charged particles, being emitted from the moon under the action of sunlight is that the constant escape of negative electrons should leave the moon with an excess of a positive charge. Because of the attraction of positive for negative charges, a positive charge on the moon would in time tend to prevent the further escape of electrons from the moon. Of course, if there are positive nuclei in space between the moon and the earth to which these electrons

could attach themselves, or were there to exist any other method of producing an electrical leakage in space, this objection would be largely removed.

With the accumulation of more radio data it should be possible to further test the validity of our hypothesis. It is somewhat unfortunate that in the case of radio waves in the broadcast band the field strengths are so attenuated in daylight hours, as also in strong twilight, that data are not obtainable for the complete lunar cycle. With the accumulation of field-intensity data for shorter waves that are not so affected, it should be possible in the course of time to apply additional tests to the theory. However, such material as has been presented suggests that, having largely solved the problems of celestial mechanics of the Newtonian era, we may now be approaching a new era of celestial electronics to which we shall soon have to give attention in our cosmic thinking.

In the next chapter we shall see how, in a rather incidental way, the moon plays a different but important part in furthering our knowledge of the ionization of the earth's atmosphere.

Chapter 8

RADIO, SOLAR ECLIPSES, AND COSMIC EFFECTS

On those relatively rare occasions when the moon, as it becomes new, passes directly between the earth and the sun, we have one of the most spectacular phenomena of nature, a total eclipse of the sun. For many years astronomers have traveled far and wide over the earth to place themselves within the shadow of the moon on such an occasion. The reason for this is that then, as at no other time, can a scientist examine in detail a curious glow or halo that encircles the sun at the moment the bright solar disk is completely covered by the moon. This halo we call the solar corona. Its photography at every eclipse is one of the chief parts of the program of an eclipse hunting expedition. The corona varies in size and intensity with almost every such occasion. Its form is known to be definitely rounder at a sunspot maximum than at a sunspot minimum. At an eclipse occurring near sunspot maximum, the corona surrounding the sun is nearly a symmetrical glow of light against a starlit sky. When, however, an eclipse occurs at a sunspot minimum, the corona extends much farther in the direction of the solar equator than it does in the vicinity of the north and south poles of the sun. In almost every photograph of the solar corona, however, one can detect streamers, or striations, radiating away from the poles of the sun suggesting ionospheric paths in the surrounding gases formed by electrons or other radiation emitted from the sun itself.

If one examines the light of the corona, he finds a brilliant green light in the spectrum accounting for much of the illumination. For many years it was known that this green light did

not correspond to that emitted by any known element in the laboratory. More recently, Edlén has shown that the coronal light may be largely attributed to an unusual state of ionization of the well-known elements of iron and nickel.

Various techniques have in recent years been employed to try to photograph the solar corona without an eclipse. Success was obtained by B. Lyot, who, with special equipment which he called a coronagraph, first photographed the brightest part of the solar corona from Pic de Midi in France in 1930. In the United States a coronagraph embodying many improvements has been set up in recent years at Climax, Colorado, under the direction of the Harvard Observatory. Results already obtained seem to indicate that there is a connection between the brightness in the lines of the coronal spectrum and the occurrences of sunspots and ionospheric disturbances. The possibility that continued observations may add a new kind of data in connecting solar activity with ionospheric predictions seems hopeful.

Quite apart from the new interest in the solar corona that total eclipses of the sun afford, solar eclipses offer a very important opportunity for adding to our knowledge of the mechanism by which the sun creates the ionization in the earth's atmosphere. At no other time is it possible for the ionizing radiation of the sun to be suddenly cut off in the middle of the day, thus affording radio investigators the opportunity to watch the effects upon communication conditions and the ionization changes which immediately take place in the atmosphere under such circumstances. The immediate withdrawal of solar radiation for a short interval during daylight hours also affords a rare occasion for comparing field strengths before and after the darkening with those obtained while the moon's shadow passes over the transmission path.

As far back as January, 1925, G. W. Pickard discovered that during the minutes of total eclipse, radio waves of such frequencies as are transmitted better by night than by day

showed a remarkable increase in intensity as the moon covered the sun. Waves of such frequencies as are generally transmitted better by day than by night showed a corresponding decrease in the intensity of the received signal. The eclipse effect was distinctly a night effect, indicating a temporary decrease in the electron density of the ionized layers as the immediate result of the screening of solar radiation of the earth by the interposition of the moon.

During the eclipse which passed over England and Norway in June, 1927, Appleton and Naismith reported likewise a partial return to night conditions during the eclipse. They deduced from their observations that the equivalent height and the reflection coefficient of the ionized layer reached their maximum values at a time agreeing to within one second with the actual time of the mid-eclipse. The apparent coincidence of the time of maximum effect upon the ionized layer with the time of mid-totality appeared to imply that the principal solar factor in the production of ionization in the ionosphere was the ultraviolet radiation from the sun. Traveling at the speed of visible light, ultraviolet radiation should produce the maximum eclipse effect simultaneously with the time of greatest visual darkness. Observations at subsequent eclipses have verified these observations, showing that the principal source of ionization from the sun must be that of ultraviolet radiation.

It will be recalled that to explain certain other solar effects on radio one has had to suppose that in addition to the ultraviolet light effects, electrons or corpuscles are emitted from the sun, particularly at times of sunspot maxima, which flood the earth's atmosphere causing a change in the ionization all around the earth and often lasting several days. Our best hypothesis for explaining the northern lights or the aurora has been on the basis of such an electron or corpuscular theory. On the assumption of such an hypothesis, Carl Störmer has shown by calculation that the paths of such charged particles would be so bent

by the magnetic field of the earth as to be carried around onto the night half and would descend in the vicinity of the magnetic pole, so ionizing the gases of the upper atmosphere as to produce the familiar brilliant lights. Such charged particles, however, emitted by the sun presumably in the vicinity of sunspots, should be traveling at a much slower velocity than the velocity of light, and it has been thought that solar eclipses which would cut off a stream of such particles from the sun should afford an opportunity for testing this corpuscular theory of ionization of the earth's upper atmosphere.

Some months prior to the eclipse of August 31, 1932, which many will remember crossed the New England States, preparations were made for making such a test. A British scientist, Dr. Sydney Chapman, suggested that while the upper ionized layer to a height of some two hundred kilometers may be chiefly ionized by ultraviolet radiation, the lower layer of about one hundred kilometers might be ionized by neutral particles emitted from the sun. Assuming such particles or corpuscles to be traveling at a velocity of only 1600 kilometers a second, he called attention to the fact that the shadow of such a stream of particles would be vastly different in its location from that of the path of the optical shadow cast by the moon during an eclipse. Taking into consideration the motion of the earth and the moon, as well as the rotation of a spot on the sun which might be emitting such particles, he calculated that four minutes would be required for such particles to traverse the distance between the moon and the earth. He estimated that the whole corpuscular shadow cast by the moon, 2,160 miles in diameter, would consume seventy-four minutes in passing a point represented by the center of the earth. The actual time of the passage of this corpuscular shadow at any given eclipse station would depend upon the location of the station, the season of the year, and the time of day at which the eclipse occurred. The important point was that the corpuscular shadow would occur at a

very different time than the passing of the light shadow and should precede it. Chapman pointed out that if the lower ionized region of the earth's atmosphere owes its ionization chiefly to corpuscles emitted from the sun, then the production of any new ions would cease during the passing of the corpuscular shadow, with a resultant decrease in the ionospheric content of the atmosphere during this period. After the corpuscular shadow passed, the bombardment of these corpuscles from the sun would be renewed, and the ionospheric content of the atmosphere would increase again.

If the ionization of the lower atmosphere, as well as that of the higher ionized layers, was solely due to ultraviolet light, the time of minimum ionization in the E layer should correspond closely to the time of central eclipse.

The eclipse of August 31, 1932, from the point of view of radio observations, was not well situated for Chapman's theory. According to his calculations, the corpuscular eclipse took place in the middle of the Atlantic Ocean. Its path lay far east of that for the optical eclipse, thus affording little opportunity for even coastal radio stations to observe effectively. Furthermore, the eclipse occurring at 19^h17^m Greenwich time took place in the middle of the afternoon in the New England States. On account of the differences in time, European radio observations had to be made under the disadvantages of sunset conditions. Radio conditions at sunset represent a transition between day and night ionization with a resulting instability in the ionosphere. Even in the United States and Canada, radio observations had to be made in the afternoon where even along the Atlantic seaboard the observers were near the extreme western limit of the corpuscular shadow.

Such results as were obtained both in the United States and in England were not indicative of any corpuscular effect being detected. A decrease of ionization observed in London between 17^h and 17^h20^m, or about two hours before the predicted time for

mid-eclipse, gave some evidence which might be interpreted as favorable to the corpuscular theory were it not for the fact that a similar effect of somewhat less magnitude was observed on the succeeding evening without any such eclipse. On the other hand, Cambridge (England) did find that the electron density in the lower layer fell to a certain critical value nearly an hour earlier on the eclipse date than on either of the adjacent control dates, an observation which was also confirmed in London. Observations at three Canadian stations gave no indication of any corpuscular eclipse. Observations by the National Bureau of Standards and others did indicate the effect of ultraviolet light in the E region of the ionosphere coincident with the time of the optical eclipse.

Kenrick and Pickard carried out an intensive investigation with stations at Portsmouth and Seabrook Beach, New Hampshire, and at Medford, Massachusetts, making control observations on that and the day following the eclipse. Measurements of the virtual height of the Kennelly-Heaviside layer or E layer from transmissions on 3492.5 kilocycles and 4550 kilocycles on the day of the eclipse, August 31, 1932, showed an abrupt fall of the F layer from around 350 kilometers to around 300 kilometers centering around the time of totality. This was a positive demonstration of ultraviolet light effect at high levels. Observations on control days before and after the eclipse showed no such effect.

Field-intensity variations made at Medford from a station transmitting in Ontario at 6095 kilocycles showed an abrupt drop immediately following the occurrence of totality. Field strengths fell below the range of the recorder about two minutes before totality, and remained too weak for measurements until about 4 P.M. No such effects were observed on August 27 and 28 preceding the eclipse. These high frequencies presumably were transmitted from the F layer. Measurements of field intensity in the broadcast band, E layer transmission, were also

recorded in Medford from station WCSH (940 kilocycles) at Portland, Maine, during the afternoon of the eclipse with control observations the day following. In this case, as might be expected, Kenrick and Pickard reported a normal rise in signal strength immediately following totality, with a subsequent drop thereafter. This is the kind of effect in the broadcast band which normally occurs after sunset when there is a rise in field intensity with increasing darkness. Such observations gave clear indication of the ultraviolet effect on the E layer. No evidence for a corpuscular eclipse was apparent in their observations.

Alexanderson, of the General Electric Company, gave special attention to obtaining evidence for or against the corpuscular theory. He made tests on 8655 kilocycles. This particular frequency was selected as one that would have a skip distance not much beyond the distance at which the observations were to be made. A type of continuous wave signal interrupted sixty times per second was utilized in the test. Each interruption was 1/500 of a second in duration. Signals were sent from Schenectady, New York, and received at Conway, New Hampshire. During tests on the afternoon previous to the eclipse, the signal was strong but confused with rapid fadings characteristic of multiple reflection, as had been expected. On the day of the eclipse, signals almost totally disappeared during the two hours preceding the optical eclipse of the sun. At about the time of the optical eclipse, the signals appeared again, first in a scattered way and then strong and continuous.

Observations were also made of signals received from Germany at approximately the same wave length. These signals were strongest during the period when the Schenectady signal was weakest. Alexanderson interprets the increase in the strength of the German signal as due to the night effect in the mid-Atlantic caused by the corpuscular shadow predicted by Chapman. It is well known that transatlantic transmissions at

these frequencies are stronger over the Atlantic Ocean at night than by day. Alexanderson's observations, therefore, appeared to give some support to Chapman's theory of a corpuscular eclipse, but the explanation is not simple as to why a corpuscular eclipse which centered in the middle of the Atlantic Ocean should affect the transmission path west of the shadow, as between Schenectady and New Hampshire. It should also be pointed out that the frequency of 8655 kilocycles used is rather a high frequency for testing transmission by way of the E layer, especially over so short a path as that from Schenectady to Conway.

Realizing the relatively unsatisfactory conditions attending the eclipse of August 31, 1932, from the point of view of observing any corpuscular shadow, a group of scientists of the University College of Science undertook observations during the "annular" eclipse of the sun visible in India on August 21, 1933. Measurements were carried out by observing the critical frequencies of upwardly directed waves which were just capable of penetrating the E. (Kennelly-Heaviside) and the F (Appleton) layers. The distance between the transmitting and receiving station was approximately seven kilometers. Frequencies were available up to 8750 kilocycles, corresponding to a wave length of thirty-five meters. From the frequency of penetration found, it is possible to calculate the ionospheric content of both the reflecting layers. Careful control observations were carried out on the day before and the day following the day of eclipse.

When the records were reduced, it was found that there was a gradual fall in the ionization of the upper or F layer for from one to two hours before the start of the optical eclipse. This was not true on either of the control days. The observations on the E layer again indicated a decrease in ionization beginning about one hour before the start of the optical eclipse. Ionization reached its minimum shortly after mid-eclipse. The control

observations made on August 20th showed a small drop in ionization corresponding to the time of day at which the eclipse began on eclipse day. The control observations on August 22nd, however, showed a rise in ionization rather than a fall during the corresponding period. Thus, again the results were somewhat unconvincing. The observing scientists themselves, Mitra, Rakshit, Syam, Ghose, believe their observations gave little indication for a corpuscular effect on E layer ionization. The results, however, showed very clearly the immediate effect of the withdrawal of ultraviolet light as the optical shadow passed. The eclipse of 1933 was much more favorable from the point of view of the location of the electronic shadow than that of 1932, since the eclipse observed in India occurred much earlier in the day than that observed in New England.

At the partial eclipse of February 3, 1935, observations made by the National Bureau of Standards yielded confirmational evidence for the ultraviolet-light effect found at these early eclipses. The degrees of ionization in both the E and F layers were found to be approximately in time phase with the occurrence of the optical eclipse.

During the total solar eclipse of October 1, 1940, observations made by Higgs in South Africa likewise yielded the expected results both for the E and F regions. A slight decrease in the ionization, preceding by an hour or more the beginning of the eclipse, suggested to the observers possible evidence for a corpuscular effect, but as the ionic density was below normal during most of the morning of the eclipse, Higgs did not believe that too much significance should be attached to the effect noted.

In spite of the war, a considerable number of scientists observed the solar eclipse of July 9, 1945, when the path of the shadow stretched from Boise, Idaho, through central Canada into Greenland, and across the Scandinavian Peninsula into Asia. Extended reports of ionospheric conditions during this eclipse have yet to be made. One account already published

reports that ionospheric observations were made at Tromsö, in Norway, where the sun was 92 per cent covered by the moon. An expected decrease and increase in the critical frequencies was noted for both the E and the F layers as the eclipse progressed. At mid-eclipse the decrease in ionization in the E layer was found to be 50 per cent, and for the lower F layer, 57 per cent. A certain tardiness was observed in the recovery of ionization of the upper F layer following the eclipse, an effect that was not observed on the following day, used as a control day for the observations.

One unusual investigation was made during this eclipse by J. T. Wilson at God's Lake, Hudson Bay. This had to do with measuring the potential of the electric field existing between the earth and a point above in the lower atmosphere. Probably few realize that, on the average, there is an electrical potential between the earth and the atmosphere. Near the ground this increases with height, and in fair weather amounts to about 100 volts per meter. On account of this potential, a small electric current is constantly flowing between the sky and the earth, as though electrons were continuously escaping from the earth. What maintains the earth's electric charge is still much of a mystery. Just how much the sun's radiation has to do with this has not been well determined. This is why the experiment by Wilson, at God's Lake, was particularly interesting. With a suitably arranged electrometer, he measured the potential gradient of the atmosphere before, during, and after the eclipse. While before totality, the potential gradient reached 150 volts negative, within three minutes after the duration of the total phase, the gradient dropped rapidly to zero, reversed in sign, and actually attained about 75 volts positive and again returned to the apparently normal pre-eclipse value.

These observations are significant, since ionospheric observations show a marked drop in the ionization of the upper atmosphere immediately accompanying envelopment in the moon's

shadow. The results of the observers at God's Lake are of interest, especially since their readings indicated a lag of three minutes between totality and the beginning of the fall of the atmospheric potential at the earth's surface. Were this potential even in part maintained by charged particles emitted from the sun, then this time lag might be indicative of the relatively slow velocity of such particles in entering the earth's atmosphere. One might hastily come to the conclusion that the corpuscles traveled at such a velocity as to consume three minutes in passing from the moon to the earth, since no change was observed until three minutes had elapsed after the moon had effectively screened all radiation of the sun from the shadow cone. If, on the other hand, the ionization of the lower atmosphere nearer the earth's surface were to be regarded as a progressive effect from the top of the atmosphere down, then such reasoning might be erroneous.

There is an important point which should be raised, however, in connection with the corpuscular theory of ionization. We must recall that Chapman's calculation of the effect depended upon the assumption that the corpuscular radiation from the sun consisted of neutral or uncharged particles. His predictions could not hold were we concerned with either positive or negative particles emanating from the sun. Unless particles emanating from the sun succeed in arriving in the region of the earth's upper atmosphere devoid of any initial or acquired electric charge, their paths will be seriously deflected as they encounter the earth's magnetic field. As Störmer has shown in connection with charged particles producing auroras, one would expect that the paths of such charged corpuscles entering the earth's atmosphere would be so far removed from the eclipse track that it would be difficult to calculate where observations should be made to detect such an eclipse effect. Probably an observing station for radio effects at or near where astronomers would locate for observing the corona would be an unfavorable region

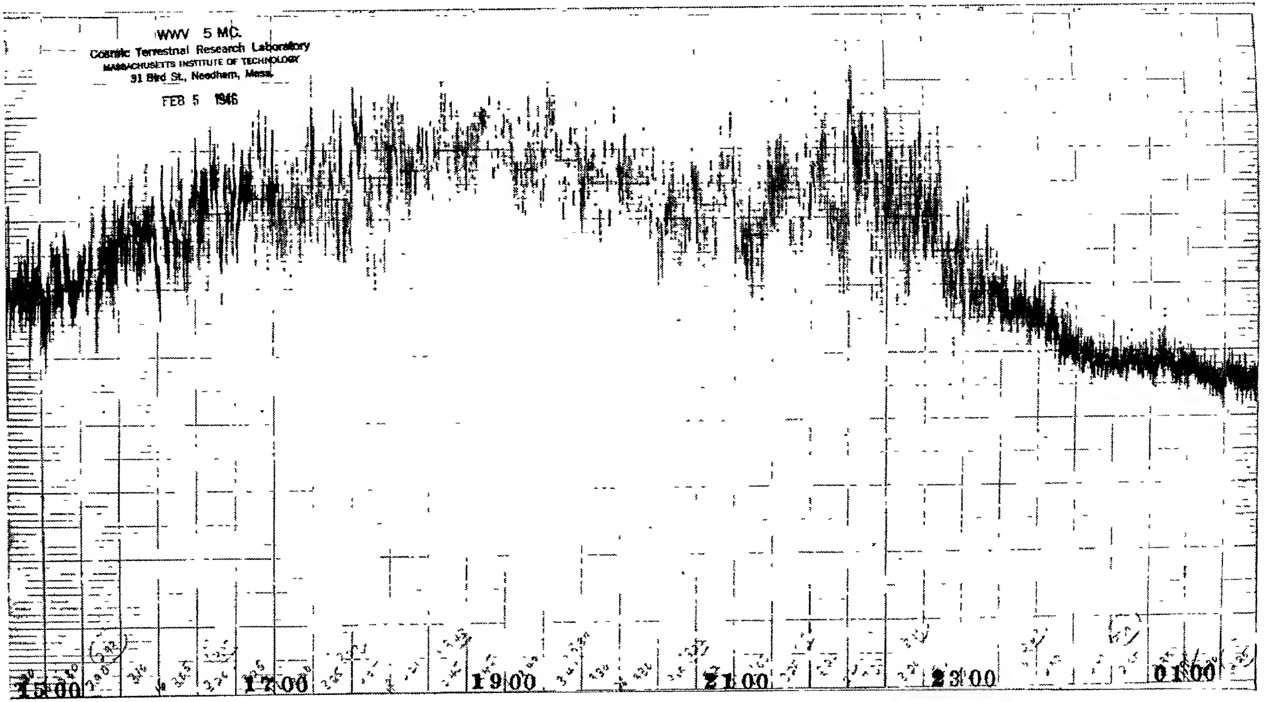


Plate V. Field-intensity curve of WWV at Needham, showing normal reception the night of February 5, 1946, preceding auroral disturbance of February 7, 1946

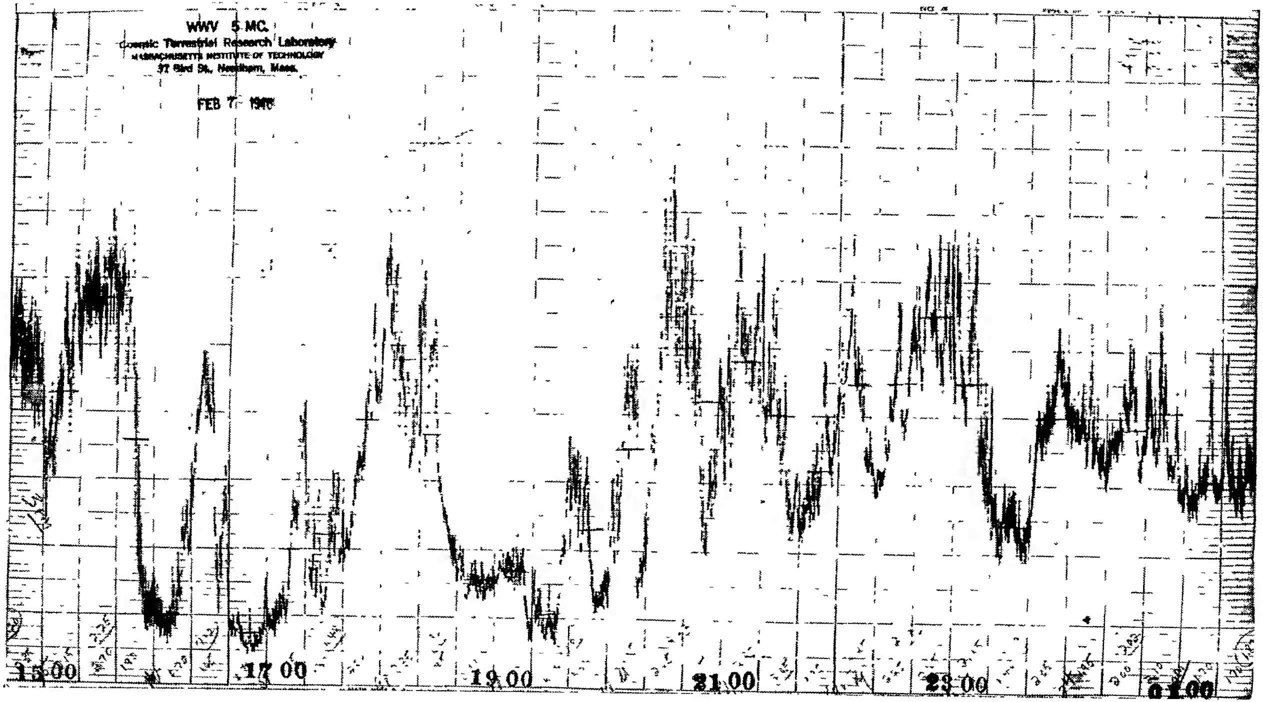


Plate VI. Field intensity of WWV at Needham on the night of the aurora accompanying sunspot of February 7, 1946

of the globe in which to observe the effect of an electronic shadow.

As has been pointed out earlier, there is considerable evidence for believing in some kind of corpuscular or particle radiation from the sun. In support of such evidence we have Störmer's theory for the formation of the aurora by charged particles entering the earth's atmosphere. Furthermore, as has been mentioned previously, observational evidence indicates a delay of a day or more after maximum sunspot activity before maximum disturbance to radio communication occurs at E layer levels. The interesting question, then, arises as to why these tests for corpuscular radiation during solar eclipses have failed. Perhaps a part of the answer to this question lies in the fact mentioned above that Chapman's assumption of neutral particles rather than charged particles has not been a correct one. Another part of the answer may come from the fact that the solar eclipse observations which gave most attention to the search for corpuscular radiation were made during the years of minimum sunspot activity. While eclipses do occur in years of sunspot maxima, the chance that large sunspots will be in evidence on eclipse day is a remote one. Perhaps at some future eclipse occurring during a sunspot maximum, we shall have such a happy coincidence. If new calculations are made on the assumption that charged particles rather than neutral particles are involved, it may be possible to predict where radio observing stations can best be located for observing such corpuscular effects as may occur. On the other hand, should such charged particles be raining into the earth's atmosphere along very curved paths at different velocities, the difficulty of predicting the region of the globe that would be most affected during the brief interruption of the total solar eclipse would be considerable. The widely extended area that could be covered by a hypothetical electron shadow is so great, as compared with the narrow track of an optical eclipse, that it makes the problem for a radio

eclipse observer far more complicated than the problems of observing the corona by the conventional astronomer. Furthermore, if the corpuscular effect to be expected is more pronounced at sunspot maximum than at sunspot minimum, the radio eclipse observer who would hunt for a corpuscular effect must wait longer intervals for eclipses favorable to his project. Such an eclipse took place on May 20, 1947. This was visible to observers in Argentina, Paraguay, and Africa. The total phase of the eclipse was of more than five minutes duration. We shall await with interest such results as may be forthcoming.

Chapter 9

SUNSPOTS THEMSELVES

HAVING GIVEN so much space to a consideration of the effect of sunspots and solar radiation on the electrical state of the earth's atmosphere, we may well pause to consider in some detail the sunspots themselves. The more we can know about their nature and their origin, the better, perhaps, we can understand their effect on the earth.

As we noted in the opening chapter, sunspots have been observed in a more or less regular fashion since the invention of the telescope in the seventeenth century. It was not, however, until 1873 that the Royal Observatory at Greenwich (England) began its extensive catalogue of sunspots, and to date over fifteen thousand groups of sunspots have been noted and catalogued since the beginning of the Greenwich observations. Today many observatories scattered around the globe make daily photographs of the sun, so that, irrespective of weather and overcast skies, there is always some observing station that can give us up-to-the-minute news on each day's happenings on the sun.

For many years the observatory at Zurich, Switzerland, a country fortunately exempt from the ravages of recent wars, has observed and collected from outlying stations and various cooperating agencies careful daily counts of the numbers of sunspots, and has expressed these in the form of an index of solar activity, frequently called the "Zurich number." The Zurich number was originally devised by the astronomer Wolf, and subsequently continued by his successor Wolfer as a measure for sunspottedness. For this reason the Zurich numbers

are sometimes referred to as the Wolf or Wolfer numbers. Realizing, through almost uncanny intuition, that a group of sunspots was more significant than a single spot, Wolf gave ten times the emphasis to the number of groups of spots appearing on the sun at a given time as he did to the individual spots present. Thus, the Zurich or Wolf number for a given day is very nearly expressed as the number resulting from adding ten times the number of groups visible to the total number of all spots that can be counted on the solar disk on any given day.

When it became necessary to compare observations made by different telescopes at different observatories, it was found desirable, in order to reduce figures to a comparable scale, to multiply the result by a factor that depended upon the size of the telescope and the acuteness of the eye of the observer. This factor, for a reasonably good telescope and a careful observer, does not differ very greatly from unity, or 1.0. Observers using small telescopes would need to use a factor a little larger than 1.0 to make comparable estimates of sunspot numbers. Where larger telescopes are employed, such as that used for solar observations at the Mount Wilson Observatory in California, this factor may be somewhat less than 1.0 in order to reduce the number of spots seen with the Mount Wilson Observatory equipment to a number comparable with the scale adopted many years ago at Zurich. It is surprising, however, how remarkably consistent are the sunspot numbers determined on such a basis, at various observatories.

A very energetic group of the American Association of Variable Star Observers, under the direction of Neal J. Heines, recently formed a Solar Division for cooperative work, chiefly among amateurs, in the observing of sunspots. At present more than thirty of these amateur observers make reports, many of which compare favorably with the results obtained by professional astronomers at the larger observatories. The or-

ganization has the advantage of covering a rather wide geographical area so that very few days of each month are lost to solar observing on account of cloudiness.

More recently there has also been adopted another method of expressing the degree of sunspottedness. This consists in actually measuring the total amount of the spotted area on the sun, and comparing this with the area of the solar disk. Sunspot areas and positions are regularly determined in this country by the Naval Observatory and other collaborating observatories. They are reported monthly, and printed in the Weather Review of the United States Department of Commerce. In Greenwich records the area of every group is also given for each day. Because the spotted area is always small with respect to the clear portion of the solar disk, areas are expressed in units of one millionth of the area of the solar hemisphere. This unit area corresponds to approximately 1,174,000 square miles. Even this is a large figure in terms of terrestrial units. Of the fifteen thousand groups catalogued at Greenwich since the beginning of the observations in 1873, only twenty-five such groups have attained areas as great as twenty-five hundred-millionths of a solar hemisphere. A group of this size covers about three thousand million square miles on the sun.

According to Nicholson, of the Mount Wilson Observatory, a careful scrutiny of all the records shows that the largest sunspot area yet reported was that of the giant sunspot of February 7, 1946. (Plate I) How long before this record will be broken subsequent to the present date of writing remains to be seen. This group included two very large oval-shaped spots with a number of smaller companions. The largest spot of this group was ninety thousand miles in diameter. If we include the associated spots, the over-all length of the group was 192,000 miles, and the total disturbed area—more than thirty times the earth's surface—measured 60,300,000,000 square miles! As this huge spot passed across the sun's disk, radio communications were

blacked out and auroras blazed their streamers across the night skies of the northern latitudes.

What is actually taking place in the heart of one of these sunspots was first made known in 1908 through a remarkable discovery by one of America's greatest scientists, Dr. George Ellery Hale, shortly after his establishment of the Mount Wilson Observatory in California under the auspices of the Carnegie Institution of Washington. By using his newly invented apparatus which he called a spectroheliograph, he was able to photograph the sunspots of 1908 in the particular light emitted by incandescent hydrogen and by calcium which composes a large part of the sun's surface. His photographs first demonstrated that sunspots were giant cyclones or whirlpools in the sun's atmosphere, similar in formation to the tropical hurricanes and whirlwinds that so often originate in the West Indies and sweep northward with devastating results. (See Figure 21.)

No ordinary telescope ever would have disclosed such detail in the heart of a sunspot. Hale's special contrivance was a combination of a moving plate and a spectroscope attached to a telescope. The photographic film moved across the image of the sun formed by the telescope, while a specially arranged slit filtered out all light except that emitted from one chemical element at a time. The resulting photographs are very different from any photograph that had ever before been taken of the sun. Large blotches of hydrogen gas and of calcium vapor were seen to be sweeping into the neighborhood of sunspots as though caught by a gigantic whirlpool. By suitable adjustment of his apparatus, Hale could photograph this whirlpool at different depths, and thus get a cross section of the vortex from the top of the disturbance well down into the solar surface.

These photographs showed that, in general, spots north of the sun's equator whirled in one direction, while corresponding spots south of the equator whirled in exactly the opposite direc-

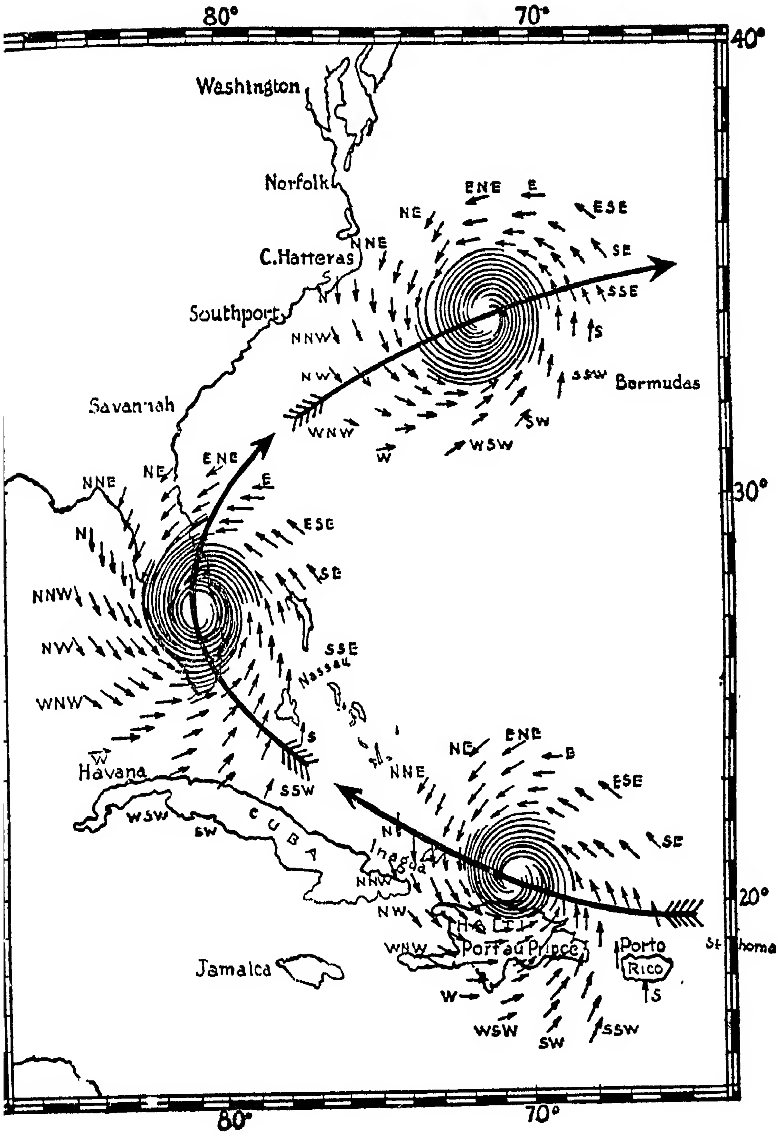


Figure 21. Spots on the sun simulate terrestrial tropical hurricanes

tion. This is again analogous to the direction of the whirl of tropical cyclones on the earth, clockwise in one hemisphere and counterclockwise in the other hemisphere. Oftentimes photographs made at Mount Wilson would show a pair of spots in which the cyclonic whirl was the expected direction in one of the pair, and of opposite direction in the second of the pair.

These discoveries gave the conception of sunspots as terrific storm centers on the sun, cyclones and hurricanes covering billions of square miles and dwarfing into insignificance the worst tropical hurricane, or the worst China Sea typhoon, that has ever happened in the world's history. Had it not been for the trick of splitting up sunlight into isolated wave lengths or frequencies by means of the spectroscope, we should never have had pictures showing the existence of these solar vortices such as we have today.

In an ordinary photograph of the sun, the light emitted by every chemical element in the sun's atmosphere is clamoring to tell us its story. The result is a rather blurred picture of the sun's atmosphere. The sunspots show up as dark regions in the ordinary photograph, only because the light-emitting power of every element in the sun is damaged in the vicinity of these violently disturbed regions.

You see, the spectroscope is very much like a highly selective radio receiving set. Remember, the sun is a high-powered station sending out light of all wave lengths and frequencies. When we look at the sun or photograph it with the telescope alone, we are, so to speak, operating a radio receiver which admits all frequencies at once. Thus we get a composite but very jumbled picture of what is happening on the sun's surface. By means of a spectroscope, the photographic apparatus may be tuned to a single frequency such as the 470,000,000-megacycle frequency that hydrogen light broadcasts. The spectroscope stills the tumult of all unwanted elements, and lets hydrogen tell its own story. It is then that we obtain clear

photographs conveying the beautifully detailed information about solar storm centers that is otherwise lost in the jumble of too many storytellers.

Another brilliant discovery came from the Mount Wilson Observatory at about the same time. It had long been known that the frequencies of light waves were distorted if there was a powerful magnetic field at the light source. When the Mount Wilson observers examined and actually measured the frequency of the light coming from the centers of sunspots, it was found to be distorted in exactly the way that light waves are distorted in the laboratory when a powerful electromagnet is placed around a source of light. Thus came the startling revelation that sunspots were not only terrific hurricanes, but also that every hurricane center was in itself a powerful magnet. This is the discovery that helped to explain the connection between the appearance of sunspots and changes in the magnetism of the earth.

What can produce these strong magnetic fields in the centers of sunspots? If the hydrogen atoms whirling around in vortices carry electric charges just as the molecules of oxygen and nitrogen in the earth's atmosphere frequently do, producing thundersqualls, then it is very reasonable indeed to believe that these hydrogen ions in the sun, circulating about the sunspot centers, really carry with them strong electric currents.

It is familiarly known that an electric current flowing around a loop of wire creates a magnetic field within the loop. This is the principle which operates in the electric generator that charges the batteries of your car.

Sunspots, therefore, appear very definitely to be generators of electricity. The evidence for it is the magnetic field which they create. By the amount of the distortion in the frequency of hydrogen light produced by a known magnetic field, one can make comparisons with the distortion measured in sunspots and thereby actually calculate the strength of these solar mag-

nets. Every day since Dr. Hale's remarkable discovery, the observers at the Mount Wilson Observatory have been recording and measuring the magnetic fields in sunspots. The magnetism in some sunspots is many thousand times as powerful as that of the earth.

The year 1912 brought the end of the sunspot cycle in which these remarkable discoveries were made. The same year was marked by the beginning of the next sunspot cycle which came to an end in 1923. As the astronomers atop Mount Wilson measured the magnetism in the few spots that could be found throughout that year of minimum (1912), they observed that the sunspots of the new cycle began to appear at high latitudes, and they were astounded to find that these new spots possessed a different kind of magnetism from that of the spots that were passing in the old cycle.

Just as there are two kinds of electricity, positive and negative, so two kinds of magnetism are recognized. The kind of magnetism which attracts the north end of the compass needle is called negative; the kind of magnetism which repels the north end, but will attract the south end, is called positive. There was actually a reversal of the magnetism in sunspots from positive to negative as the old cycle passed into the new. (See Figure 22.)

It was therefore exceedingly interesting to watch what would happen in the year 1923 when another sunspot cycle came to an end and a new one again started. True to expectations, the magnetism of the sunspots reversed again. This led Dr. Hale to announce that perhaps the real cycle in sunspots which should be adopted was one of twenty-three years rather than the usually accepted one of eleven and a half years. The reversal in the magnetism with each successive cycle showed that some twenty-three years could be expected to elapse between the time when sunspots of a given kind of magnetism put in their appearance and the return of the beginning of an-

other cycle of sunspots with the same kind of magnetism again. On this supposition, each eleven-year maximum in the solar cycle is but a half of a complete period.

It seems probable that the powerful magnetic field developed in sunspots may have much to do with the ejection of electrons,

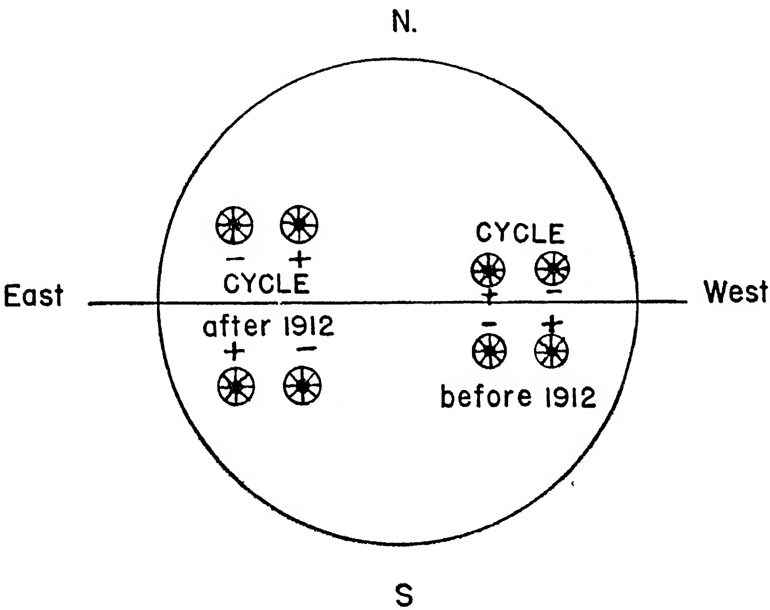


Figure 22. The magnetic polarity of sunspots reverses with the change in the sunspot cycle

charged particles, or corpuscles which we believe speed from the sun to the earth; particles that, on encountering the earth's atmosphere, cause the damage to radio communications and produce the northern lights.

The fact that, as a general rule, sunspots appear to have passed the center of the sun's disk before the maximum effect is felt on the earth, suggests that such particles as may be emitted from sunspots travel at a considerably slower ve-

locity than that of the ultraviolet light that in general is responsible for the greater part of the ionization of our upper atmosphere. It has also been noted that the greatest disturbance in the earth's magnetism, in general, occurs from one to four days after a spot has passed its central position on the sun.

Another reason why eclipse observations have failed to show that corpuscles are emitted from the sun may be due to the fact that such particles are not ejected radially from the sun, as has been assumed in the calculations. If these emitted particles have electric charges when they leave the sun, or pick up charges as they are ejected from sunspots, their paths may be seriously distorted by the magnetic field of the sunspots themselves. This, in turn, would account for the fact that often sunspots will appear on the sun with no comparable magnetic or radio disturbances taking place on the earth. Under such circumstances the paths of the ejected particles may be so distorted when they are emitted from the sunspots as not to encounter the earth at all. We must remember that the sun is a million times as large as the earth, and that the size of our little planet as seen from the sun would appear as big as a pinhead seen at a distance of thirty feet from the eye.

We might, perhaps, think of a volley of corpuscles or charged particles being emitted from sunspots somewhat in the way that jets of water are sprayed from a rotating lawn sprinkler. On account of the distorting effect of the magnetic field in the sunspots, the orifices in our analogous lawn sprinkler may be irregular in their position and shape. Whether or not a given plant gets its quota of water will depend much on the way in which the stream is started, as well as the position of the plant with respect to the sprinkler. As streams of particles from sunspots may sometimes swing high or low as they pass the central meridian, you can see that the earth may not always be in a position to receive even a part of the stream of corpuscles ejected. Under such circumstances, then, a sunspot of consider-

able size might pass across the solar disk without any noticeable effect on the earth.

On some occasions magnetic disturbances and even displays of the aurora have occurred after a spot has crossed the solar surface and, by virtue of the sun's rotation, has actually disappeared around the edge of the sun. It seems possible that under such circumstances a stream of particles ejected by the spot may have been so curved at the outset that the magnetic field of the spot itself had actually bent the stream around toward the earth's direction after the spot ceased to be visible on the front side of the sun.

We have no way at present of knowing any preferential direction in which particles from sunspots or adjacent areas may be emitted. If we averaged a great many possible directions of emission, we should find statistically that the average direction for a large number of cases would be radially away from the sun. This explains why, when we statistically examine a large amount of sunspot data through a number of years, we find from our data that the magnetic and atmospheric disturbances on the earth have most often occurred on days when spots have averaged positions near the central region of the sun's disk. As has been remarked earlier, sunspots appear at lower latitudes on the sun, that is, nearer the solar equator, as the sunspot cycle progresses. For a given amount of sunspottedness, the chances, therefore, are greater for more radio disturbances and displays of the aurora immediately following a sunspot maximum than before one. We noted this effect in our statistical study of auroral occurrences.

With the invention of the spectroheliograph, it became possible to observe other phenomena on the surface of the sun closely related to sunspots. Bright cloud-like patches occur all over the sun. Unusually brilliant displays often accompany a sunspot group. The spectroheliograph shows that these are composed of masses of hydrogen and calcium floating in the

high atmosphere. These bright patches are technically known as *flocculi*. When a sunspot group is seen near the edge of the sun, which is somewhat darker than the center of the disk, these white patches can often be seen in an ordinary telescope in the neighborhood of sunspots. Before the invention of the spectroheliograph these were called *faculae*. They now appear to be identical with the flocculi. Often they will remain relatively inactive, and again at times they will rapidly expand, indicating that something in the nature of a terrific explosion of hydrogen gas has occurred. When seen extending from the edge of the sun, they are identical with what has long been observed during solar eclipses as prominences or protuberances. Sometimes they rush outward from the sun at terrific velocities attaining heights 100,000 or 200,000 miles above the solar surface in less than an hour's time. It is such explosions that we may picture as in the nature of a solar atomic bomb. They are undoubtedly responsible for the intensive flares of ultraviolet light that can so quickly cause a radio blackout on the half of the earth directed toward the sun. These brilliant white patches can occur independently of any visible sunspots. They are, however, always more numerous and violent at times when sunspots are most numerous. Frequently, as in the case of the great spot of February 5, 1946, they are intimately associated with the sunspot group itself.

Many improvements in the construction and technique of photographing the sun have been made since the invention of the spectroheliograph. Probably the greatest single advance in this direction is due more to Dr. Robert R. McMath, of the McMath-Hulbert Observatory of the University of Michigan, than to any others we might mention. Dr. McMath is a skilled engineer and manufacturer, with a passionate interest in astronomy. After applying his engineering knowledge and skill to devising suitable means for making motion pictures of the moon, he turned his inventive genius to the very much more

difficult problem of photographing sunspots and solar explosions in action. His invention was essentially the application of the principle of the kinetoscope, or motion-picture camera, to the spectroheliograph in a way to get action pictures of the rapid changes taking place in the atmosphere of the sun around sunspots. Dr. McMath logically coined a name for his new instrument. He calls it a spectroheliokinematograph (*spectro-helio-kinemato-graph*). (Plates VII and VIII)

The excellent films which have been obtained at the McMath-Hulbert Observatory, near Pontiac, Michigan, have revealed such a wealth of information on solar explosions as to change completely many of our mechanical ideas as to what is happening on the sun. In many of these motion-picture films one not only sees huge volumes of hydrogen gas rapidly spurting spaceward, but in many instances one sees the downfall of huge volumes of luminous gas into the sun's surface. In some of the McMath films, clouds of incandescent hydrogen, previously invisible, are seen to form thousands of miles from the sun's surface, and then descend violently into the surface of the sun. One can well imagine a high state of ionization to accompany such exhibitions of incandescence. Certainly we are dealing with solar electronics on a gigantic scale.

All of this leads us to wonder how extensively solar ions are ejected into space. Perhaps here is the clue to the curious streamers and striations in the solar corona seen on occasions of total eclipse of the sun. It takes little stretch of the imagination to believe that we shall ultimately find many of these ions in interplanetary space. We may well believe that the earth is constantly under bombardment from such a source. One recalls, in this connection, certain comets that have occurred at the time of sunspot maximum, such as the celebrated Morehouse Comet of 1908. This comet showed fitful changes in the illumination of its tail, resembling the wave-like undulations often observed in the weird lights of the aurora. Perhaps on

such occasions ionized particles from the sun, streaming into the tenuous gases of the comet's tail, could well account for this queer behavior on the part of such comets, not otherwise explainable.

With the advent of radar and ultra-high frequency radio technique, microwaves have already been received at the earth that appear to be of solar origin. Recently, Pawsey, Payne-Scott, and McCréady reported on investigations made in October, 1945, near Sydney, Australia. These observers not only detected radio waves from the sun at a frequency of 200,000 kilocycles, but actually measured them and found a close relationship between the strength of these waves and the number of sunspots. They attributed this solar static to gross electrical disturbances in the sun's atmosphere, analogous to thunderstorms. Thus we see that the outgrowth of new radio equipment resulting from researches in the war effort are already furnishing us with new tools for studying the nature and effects of even sunspots themselves.

Sir Edward Appleton, of London, to whom we owe the discovery of the F layer (sometimes called the Appleton layer), has been another active worker in the investigation of microwave emissions from the sun. Dr. Appleton and his co-workers have reported emissions of frequencies from the sun in the 50-megacycle band. Report of similar solar "noise" received at 44.9 megacycles at Laurel, Maryland, have stimulated further investigations at these frequencies.

A very large group of sunspots appeared on the sun between March 5th and 15th, 1947. This was the return of the largest group on record, which appeared during the first week of February in 1947. This presented an excellent opportunity for checking the findings of others as to the correlation of solar radio noise with sunspots. The Cosmic Terrestrial Research Laboratory at Needham, utilizing a single dipole directed broadside to the sun and tuned to the 50-megacycle band, recorded

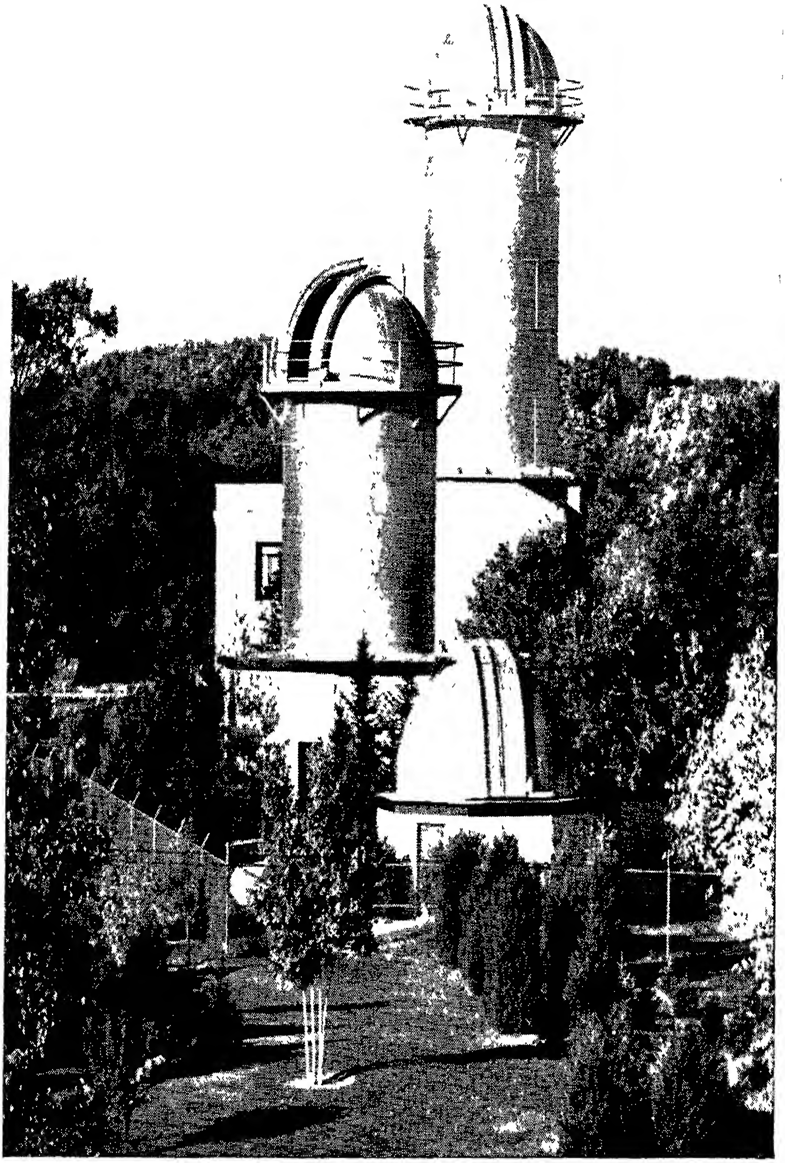


Plate VII. Solar Towers of the McMath-Hulbert Observatory, University of Michigan

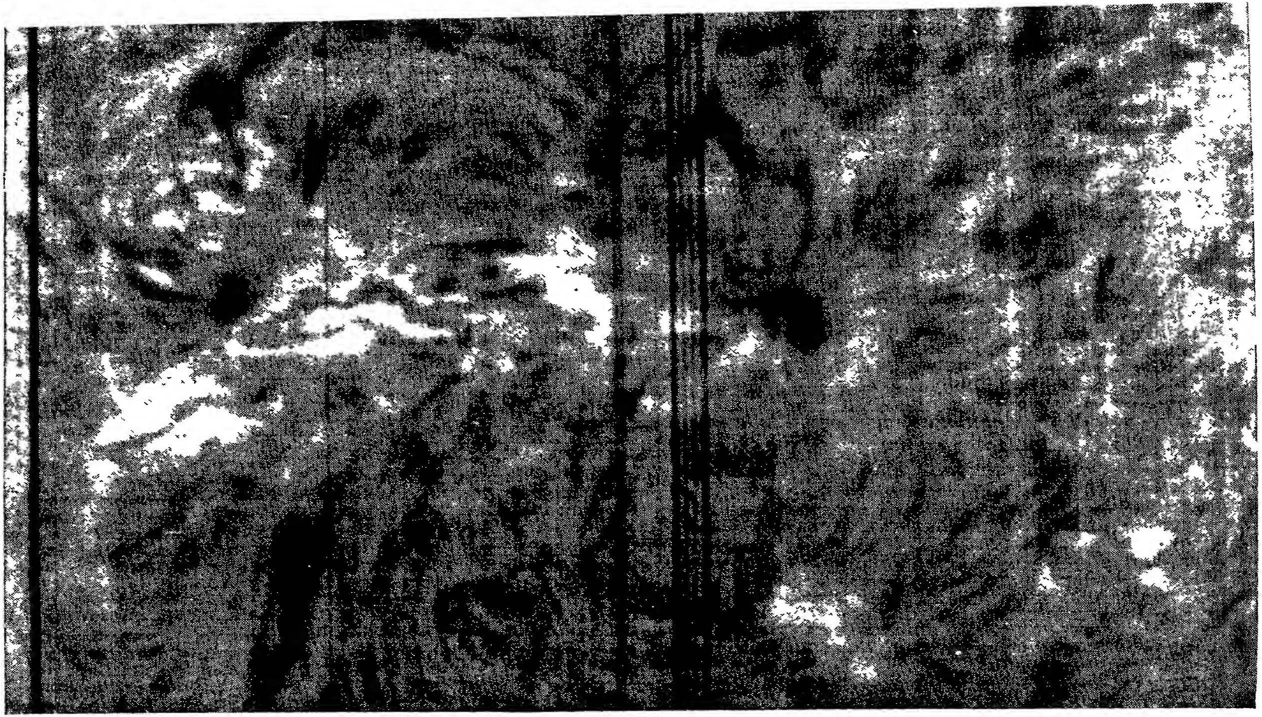


Plate VIII. Spectroheliogram showing vortical whirls in the vicinity of sunspots photographed at the McMath-Hulbert Observatory

prolonged bursts of solar origin accompanied this large sunspot group. The receiving equipment was tuned to 45 megacycles as a convenient frequency clear of any broadcast interference. The heaviest bursts occurred on March 9th, 10th, and 13th, and were of the order of two microvolts or more at the receiver. Tuning tests made during these bursts indicated broad band emission. It appears possible that with further improvement of apparatus, scientists may yet find a new index of solar activity through the measurement of the sun's radio-wave emissions. Unlike the usual telescope, a microwave telescope can "see" the sun through clouds, for microwaves at these frequencies readily penetrate our atmosphere.

Various attempts have been made to relate given radio and magnetic disturbances to the location of individual spots on the surface of the sun. C. N. Anderson of Bell Telephone Laboratories has attempted to relate terrestrial disturbances to the appearances of particular sunspots for intervals of from a few days to as much as three months after the origin of the spot in question. To predict how near a given spot, when first seen on the eastern edge of the sun, may come to the sun-earth line, we must take into account the sun's rotation about an axis inclined 7 degrees to the plane of the earth's orbit. This inclination of the solar axis results in different paths which the spots will apparently pursue across the sun's disk as the sun rotates.

In Figure 23 there is represented the location of the sunspot zones as the sun's surface presents itself to the earth for each month of the year. These diagrams are drawn so that the point N always represents the north point of the sun directed towards the north pole of the heavens. The solar axis, as seen from the earth, coincides very nearly with this north-south line in January and July; but in January, the north end of the sun's axis is tilted away from the earth, whereas in July it is tilted toward the earth. This can be inferred from the direction of the curvature of the sun's equator and that of the boundary lines

of the sunspot zones, in both the northern and southern hemispheres. In April it will be seen that the solar axis is at a considerable angle to the north-south line, the north point inclining toward the west. In October the solar axis is tilted so that its

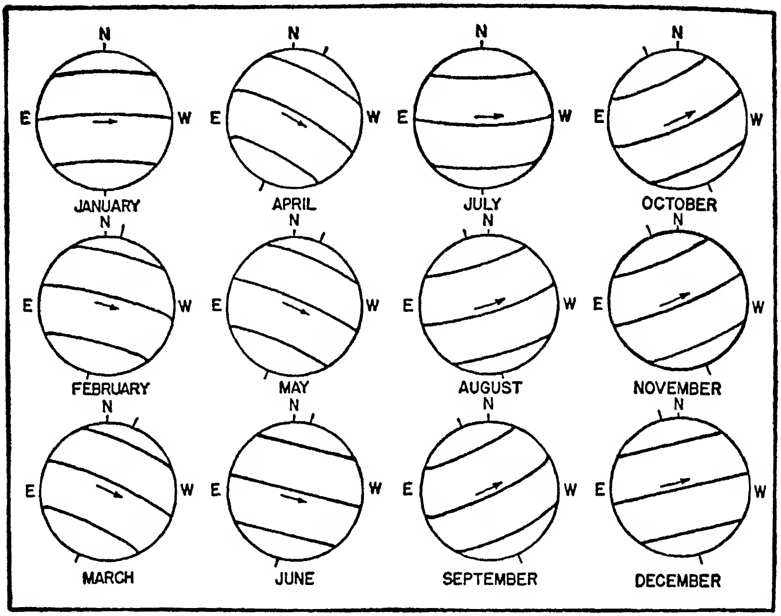


Figure 23. Positions of sunspot zones and solar axis for each month of the year. (Arrow shows direction of solar rotation.)

north end is inclined a similar amount to the east. It is only in June and December that sunspots transit the sun's disk in sensibly straight lines. By referring to this chart, a sunspot observer noting the location of a new spot appearing on the east limb (or edge) of the sun may visualize, in advance, how near the center of the disk, or the sun-earth line, the spot will be carried by the sun's rotation. One may estimate that on the average it will take thirteen days for the spot to be carried from the east to the west limb of the sun.

We have already remarked, in connection with auroral displays, that magnetic and radio disturbances are more often experienced just after a given spot has crossed the central meridian passing through the solar axis. It is statistically true that the nearer the spot passes the center of the sun's disk, the more likely we are to experience terrestrial disturbances. This generalization, however, cannot always be applied to any given spot or group of spots for reasons already discussed in this chapter.

Chapter 10

THE ORIGIN OF SUNSPOTS

One of the most puzzling problems in connection with sunspots is the question of their origin. It seems surprising that in spite of the fact that sunspots have been observed for over three hundred years, we do not yet know what makes them. If we knew what was the ultimate cause of sunspots, it would probably help very much in solving the mystery of the solar cycle and in predicting the future behavior of the sun. Of course, the spots are fundamentally due to atmospheric disturbances in the surface layers of the sun, but whether or not the cause of these disturbances is to be found entirely within the sun itself may still be a debatable question. The periodic nature of the recurrences of sunspots has suggested to some that the planets in some way were the disturbing bodies, but, so far, failure to predict accurately the activity of sunspots on the basis of planetary cycles has led some astronomers to believe that the fundamental cause of sunspots is to be found entirely within the sun itself.

Any complete theory of sunspots must obviously explain not only why they arise at the more or less irregular intervals of eleven years, but also why the first spots of a new series appear in high solar latitudes. It must also account for the slow progression of the spots toward the solar equator as the sunspot cycle advances. Furthermore, since we now know that the magnetic character of spots changes from one cycle to the next, an explanation is needed for the change in polarity of sunspots in alternate cycles.

To account for many of these observed phenomena in con-

nection with sunspots, a rather elaborate theory was advanced some years ago by a Norwegian meteorologist, Professor V. Bjerknes. On theoretical grounds, Bjerknes supposes that there is an atmospheric circulation taking place between the outer surface of the sun and the interior, in such a way that in the outer layer of the solar atmosphere the gases are flowing from the poles to the equator. Near the equator they fall below the surface, and then travel northward to high latitudes. Gaining temperature, these subsurface currents rise again to the surface around latitude 40° on the sun, then move southward to the equator, gradually cooling until they fall again into the interior as they reach the solar equator again.

Accompanying this circulation on a gigantic scale, Bjerknes postulates, the gases are caught in secondary whirls which extend in a kind of tubular formation resembling that of a hollow rubber hose engirdling the sun in parallels of latitude. As this tubular formation is carried southward toward the equator, it is now and then forced to the surface of the sun where it breaks into two segments, the upper ends of the tube appearing as a pair of sunspots. Since the circulatory motion of the gases in the tube will presumably persist even after this tubular affair has been broken at the surface of the sun, we should find the circular cross sections of these tubes appearing as vortices rotating in opposite directions. This is in accordance with the usual facts about bipolar, or double, sunspots.

Occasionally, this scientist thinks, one section of the tube might be so disturbed as to make no definite appearance on the sun, and we should have as a result but a single spot. As the tubular vortex is carried toward the equator, it is obvious that when it breaks through the surface, the resulting spots will be seen at lower and lower latitudes. When this circulating tube of gas approaches the parallel of the solar equator, it sinks beneath the surface. Thus a cycle of spots would vanish at the equator.

The author of this theory thinks that probably another vortex rotating in the opposite direction exists in the lower region, and that this is carried northward. With the heating of this region, this second rotating tube rises to the surface at about latitude 35°; when it breaks through it will form a sunspot or two with vortices rotating in the opposite direction from those of the previous cycle. On the basis of this theory it would take eleven years for a given tubular vortex to descend from high latitudes to the equator, meanwhile bringing to the surface the second tubular vortex for the start of the next cycle. Twenty-two years, therefore, would elapse between the appearance of one of these vortices at the surface and another one rotating in the same direction.

While Bjerknes thus accounts for many of the well-observed peculiarities of sunspots by this theory, he can give no satisfactory explanation of the origin of these circulating tubes of gas, nor is any attempt made in his theory to account for the eleven-year periodicity, together with the slight variation in this eleven-year interval.

Many astronomers who believe that the origin of sunspots is associated with the heating and cooling of the gases within the solar sphere incline to the idea that irregularities in the period are inevitable, and that it is probably useless to attempt to predict variations from it. There are many variable stars in the sky which change brightness more or less periodically, but with such uncertain intervals as to make the prediction of the variations exceedingly difficult, if not impossible.

In connection with the origin of sunspots, it is most important to remember that the sun rotates more rapidly near the equator than near the poles. If, as in Figure 24, we draw a series of darts along the central meridian of the sun, and let the position of the arrowheads represent the subsequent positions at the end of one rotation of the sun's surface at latitude 40°, we see at once the skewing effect produced by the acceler-

ated rotation as we approach the sun's equator. In consequence of this there must be a continuous slipping between the atmospheric gases in the lower zones against those circulating less

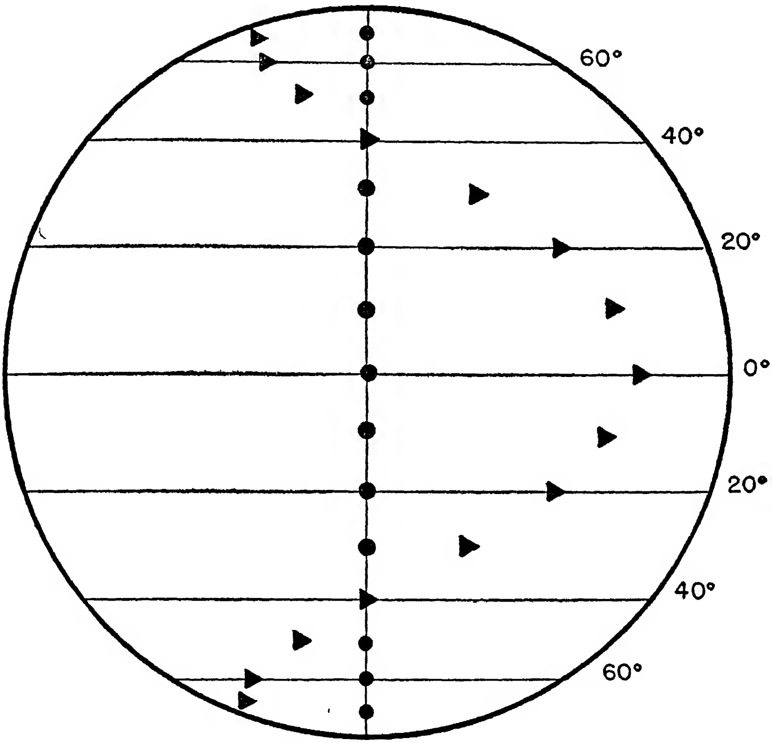


Figure 24. Illustration of the sun's variable speed of rotation. If the line of dots represents positions on the sun at the beginning of rotation, each dot will assume the position of the arrowheads at the end of one complete rotation at solar latitude forty degrees

rapidly in the higher latitude zones. This in itself should be conducive to the formation of eddies. We have all noted how rapidly moving water in the center of a stream slips past the more leisurely flowing currents near the riverbank, often causing whirlpools and eddy currents.

If we compare conditions on the earth with conditions on the sun, we see that in our own atmosphere, tropical hurricanes and cyclones for the most part occur at about the same latitudes on the earth as do the sunspots on the sun. So far we have no explanation for the speeding up of the sun's rotation as the sun's equator is approached.

Many scientists who have attacked the problem of the origin of sunspots have believed that outside forces acting on the sun are primarily the cause of sunspots. If the planets circulating about the sun are possible sources of disturbances in the sun, then we may well consider to just what extent planets could be expected to produce any effect upon the gases in the sun.

The planet whose period of revolution about the sun comes nearest to the eleven-year solar cycle is Jupiter. Jupiter revolves about the sun in 11.8 years. The average length of the sunspot cycle, however, is but 11.2 years. This difference of more than half a year is so great that it does not appear easy to assign to Jupiter alone the cause of the disturbances on the sun. The usual assumption in favor of planetary influences on the sun's atmosphere is that the attraction of the planet for the sun causes tides in the solar atmosphere, as the moon causes tides in the oceans of the earth.

In a simplified picture of ocean tides, the moon's gravitational pull on the oceans results in a bulging of the water on two opposite sides of the earth. As the earth rotates, a given part will therefore encounter two high tides and two low tides in each rotation of the earth with respect to the moon. To be sure there is also a monthly tide, due to the fact that the moon is for a part of the month north of the earth's equator and for a part of the month south of the earth's equator. There is also unusually high water at the time the moon is new or full, for then the attraction of the moon and the attraction of the sun on the water of the earth are acting to reinforce each other.

Carrying this earth-moon analogy over to the problem of tides

in the solar atmosphere caused by Jupiter, we should expect disturbances of the sun to occur twice during each rotation of the sun. It is difficult to see how the revolution of Jupiter in its orbit once every twelve years could produce a tide only once in this interval, even assuming that the period of Jupiter and the period of the sunspots were the same.

To be sure, Jupiter's orbit is a bit eccentric, so that it is sometimes nearer the sun and sometimes farther from the sun than its average distance. The change in its distance, on the other hand, is a little less than 5 per cent. The distance of Jupiter from the sun is 5.2 times the earth's distance from the sun, or approximately 484 million miles. Were Jupiter no bigger or no more massive than the earth, its effect on the sun would appear insignificant. Jupiter, however, weighs approximately 317 times as much as the earth, so that, on account of its mass alone, its effect on the sun is 317 times as great as that of the earth.

Now it is easy to show mathematically that the tide-raising force decreases with the cube of the distance, so that the total effect of Jupiter on the sun may be only a little more than twice that of the earth. The variation in this tide-raising force, on account of the changing distance of the planet from the sun, is six times as great with Jupiter as it is with the earth.

If Jupiter has an effect on the sun, it is obvious that the other planets likewise must influence tides in the solar atmosphere. This influence will in each case vary as the mass of the planet and as the inverse cube of the distance.

Various attempts have been made to try the combined effects of the planets. One of these that attracted attention at the time was that of the late Professor E. W. Brown, of Yale, who in 1900 called attention to the fact that approximately every 9.93 years Saturn is in line with Jupiter and the sun, so that the tide-raising force of Saturn, which is approximately one third that of Jupiter, is added to Jupiter's effect. He com-

bined this 9.93-year interval between conjunctions and oppositions of the planets with the period of Jupiter's revolution about the sun, which is 11.86 years, and found that he could reproduce most of the times of the occurrences of maxima of sunspots. By 1900, however, his curve deviated so much from the sunspot curve that the author himself expressed doubt as to the reality of the agreement. Curiously enough, the subsequent maxima of 1906 and 1917 came very close to the times which would have been predicted from Brown's assumption. However, the next maximum of 1928 would have been very far out.

It may be mentioned that in some of the minor fluctuations in the sunspot curve there is at times a very marked interval of twelve to fifteen months between secondary maxima. This was particularly conspicuous during the solar cycle from 1923 to 1933. It is perhaps worth noting that fifteen months, which are approximately four hundred and fifty days, almost exactly correspond to two revolutions of Venus about the sun, the period of Venus being two hundred and twenty-five days. This is also very nearly equal to five revolutions of Mercury about the sun. One may say with a fair degree of approximation that Mercury and Venus come together in the same longitude once every fifteen months. The planets Mercury and Venus, however, pass each other at some point once every one hundred and forty-five days, or at nearly five months' intervals. Now on account of the closeness of both Mercury and Venus to the sun, their tide-raising effect is very appreciable, the effect of Venus being nearly the same as that of Jupiter.

Birkeland made an exhaustive study of the sunspot curve and the effects of Jupiter, the Earth, and Venus. In this way he could account not only for many of the major maxima of sunspots, but also for many of the minor fluctuations. But in applying his results over a long period it is found that, as is so

often the case, actual minima of sunspots occur sometimes when one would suppose on his theory that maxima should take place.

In 1906 Schuster published a most exhaustive paper in the *Philosophical Transactions* of the Royal Society of London which should be studied by anyone who is interested in further details of periodicities in sunspots. From a careful analysis of many years' records, he found various periodicities, none of which corresponds exactly to the periods of any of the planets.

The fact, however, that periodicities in the sunspot curve do not agree with periods of revolution of the planets about the sun does not appear to me as necessarily excluding planetary influences. An important point which seems to have been overlooked thus far in all such investigations of tidal action is the effect of the sun's rotation and that of any natural period of oscillation of the solar atmosphere. On the basis of any accepted tidal theory, one would expect that each planet in turn would raise tides, however slight, in the solar atmosphere approximately equal and opposite. For comparative purposes, the following table shows the distances and masses of the first seven planets, together with their effective tidal forces at the sun.

TABLE OF TIDAL EFFECTS OF THE PLANETS

Planets	Distance	Mass ($\times 10^{-6}$)	Tidal Force	Period of Revolution (Years)
Mercury	0.387	0.20	1.10	0.241
Venus	0.723	2.5	2.11	0.615
Earth	1.0	3.1	1.0	1.000
Mars	1.52	0.32	0.03	1.881
Jupiter	5.20	952.	2.17	11.862
Saturn	9.54	286.	0.11	29.457
Uranus	19.2	44.2	0.02	164.783

In this table the distances of the planets are expressed in terms of the earth's distance from the sun as unity. The masses of the planets are expressed in terms of millionths of the sun's

mass. The column headed "Tidal Forces" represents the ratio of the mass of each planet to the cube of its distance from the sun. It will be seen from this table that Venus has almost the same tide-raising force as Jupiter, and that Mercury and the Earth have tide-raising forces nearly half as great. The effect of Saturn is only one tenth that of the Earth. The planets beyond Saturn could yield only negligible effects.

The raising of tidal waves on the sun by the planets would tend to set the whole solar atmosphere into oscillation. We should expect such atmospheric waves to travel around the sun at a speed that would depend upon the density of the solar atmosphere and the gravitational attraction of the sun at its surface. Each planet in turn would, of course, start its own peculiar tidal oscillation. The composite tidal wave at any moment would therefore depend upon the positions of the planets in respect to one another and to the sun.

As the sun rotates, carrying the atmospheric particles past the point of major attraction, successive pulses would be increasing the amplitude of the waves so long as the period of oscillation of the atmosphere was comparable with the intervals between successive pulses. In this way it is possible that even the slight tide-raising forces of the planets could in the course of time set up a major oscillation in the sun's atmosphere, very much the way in which synchronized footsteps of a regiment may set a steel bridge asway. Perhaps a homely analogy may clarify the picture.

Off the Yacht Club at Manchester-by-the-Sea I have a forty-foot cabin cruiser anchored. It is of sufficient tonnage that ordinary movements about the boat do not perceptibly set it in motion. Sometimes, as a matter of amusing experiment, I have stood in the cabin astride the fore-and-aft line and allowed my weight to fall alternately first on one foot and then on the other. Now, the weight of one hundred and sixty pounds pressing on the floor of a fifteen-ton boat, a foot from the

fore-and-aft line, produces of itself no perceptible list. Knowing, however, the natural period of roll of the boat, and using this as an interval for alternating the pressure from right to left, I can make the boat roll violently in a very few minutes. It can be stopped equally quickly by reversing my movements, thus making the small force which I can exert oppose the natural roll of the boat.

Suppose, now, that the solar atmosphere has a natural period of oscillation similar to that of the boat, and that it encounters the slight tidal force of Jupiter twice each rotation of the sun, or approximately once every thirteen days. If the natural period of vibration of the sun's atmosphere is close to the thirteen-day period, then in the course of time the solar atmosphere will become violently agitated so that convection currents arise within it, causing eddy currents and whirlpools which break out in sunspots. The time that it will take to start the solar atmosphere into a period of maximum oscillation after it has been in equilibrium will depend upon how closely the interval between pulses of the tidal force corresponds to the natural period of oscillation of the atmosphere. It is conceivable that months and years may be necessary for the accumulation of a sufficient number of weak pulses to get the sun's atmosphere into the maximum disturbed state. If the intervals between the tidal-force pulses are not in exact agreement with the free period of oscillation of the solar atmosphere, the disturbances will subside again until equilibrium is attained, after which another period of oscillation will grow to maximum with a subsequent subsidence.

To return to the boat analogy, if the interval between the pressure exerted to the right and left of the fore-and-aft line of the little ship is somewhat less than the natural period of roll of the vessel, a long time will elapse before the boat takes on its maximum oscillation. If we continue to experiment, we soon find that the difference in the intervals between the

applied force and the intervals of a complete cycle of roll will work against the very oscillations which the imposed forces set up. The roll of the vessel will gradually die down until it is stationary, and then will start up again in another cycle. The intervals between the times of the maximum roll of the vessel depends very definitely on the difference between the length of the interval of my alternate foot pressure and that of the successive rolls of the boat. The interval between times of maximum roll may be very great indeed compared to the natural period of the roll or of the interval between my alternating foot pressure. Now, let us carry our analogy back to the sun.

Twice every revolution of the sun, a given region of the solar atmosphere encounters the tidal stress of some planet. This interval, as we have already stated, may not be very far from thirteen days. It will be longer than thirteen days for Mercury, which is changing its position rather rapidly on account of its fast orbital motion; and it will be very much nearer thirteen days for Jupiter and Saturn, which are so far out that their leisurely orbital motion makes very little difference in their position with respect to the sun in two week's time. A similar situation will hold for Venus and the Earth.

From the point of view of the tide-producing power, Venus and Jupiter are about equal. On the other hand, Venus moves so rapidly around the sun, as compared with Jupiter, that the tidal pulses created by Venus may be encountered at too long intervals to agree very closely with the natural period of oscillation of the solar atmosphere. Jupiter, on the other hand, moving much more slowly in its orbit, raises tidal bulges in the sun's atmosphere which will be encountered at but a little more than thirteen-day intervals. If, therefore, the natural period of oscillation of the solar atmosphere is such as to favor a thirteen-day interval, Jupiter will have by far the greater effect, although it may take years for its feeble tide-raising force to bring the

solar atmosphere into maximum oscillation. We might expect that the intervals between maximum solar disturbances, therefore, should be nearly equal to the period of revolution of Jupiter about the sun; but to be exactly the same would be a most remarkable coincidence.

It would seem that real progress in predicting sunspots from planetary effects may yet come, if, in addition to analyzing the periods of planetary motion, one takes into account the natural periods of oscillation of the solar atmosphere as well.

One might add to this somewhat speculative hypothesis the fact that the zone for maximum horizontal tidal stress on the sun occurs near 45° latitude, a region not far from the zone where the first sunspots start at the beginning of a cycle.

If we suppose, then, that it is in these zones of latitudes either side of the solar equator that the oscillatory disturbances are started, there might be a general movement of the particles in the solar atmosphere from these zones toward the equator in either hemisphere, just as there is a tendency due to the tides of the ocean for the water from 45° latitude to flow toward the equator, the region that, on the average, is most nearly under the moon.

As the disturbances start in these zones on the sun and move toward the equator, vertical whirls would gradually be generated as the cross current meets the region of the sun's atmosphere that is moving rapidly westward. These eddies would break out as sunspots in latitudes lower than the 45° zone. This would be in general agreement with the latitude of the first sunspots breaking out in new cycles. The oscillatory motion of the solar atmosphere would gradually be damped out by the lack of complete conformity between the intervals of the pulses of the planetary tidal forces and the natural period of oscillation of the sun's atmosphere. The spots, therefore, might be expected to peter out at the equator at the end of this interval. By the time of disappearance of this series of oscillations, the

continued pulses would start a new cycle at high latitudes, thus ushering in the new sunspot period.

Another factor which may enter the situation is the variable rotation of the sun. It may be entirely possible that the period of rotation in latitude 45°, which is about twenty-six and a half days, is more favorable for the encountering of the planetary tides twice each revolution than is the shorter period of rotation which is experienced at the sun's equator. This would be an argument in favor of spots starting at high latitudes and petering out at low latitudes. There would, you see, be a slowing down of the oscillations as they move into the equatorial region where the shortened period of the sun's rotation kills the natural vibrations which have been set up. When someone has more completely worked out the free period of oscillation of the sun's atmosphere, such a hypothesis may be put to a more rigid test.

The fact that the atmosphere of the sun in which the spots occur may be a thousand times more tenuous than that of the earth's atmosphere favors a natural period of oscillation of at least several days. Furthermore, the effect of the gravitational attraction of the sun upon the particles in its atmosphere is very considerably minimized by the outward pressure of radiation coming from the interior of the sun. This is another reason for believing there may be natural periods of oscillation of relatively long duration.

At this point mention should be made of certain other phenomena that may contribute evidence for the action of planets on solar activity. In 1907, Mrs. A. S. Maunder called attention to what has subsequently sometimes been called an "earth effect." Extended observations have shown that for some strange reason more sunspots are born on the side of the sun away from the earth than on the face of the sun, and furthermore, that more spots appear to die on the face of the sun toward the earth than on the hemisphere turned away from the earth. A. Schuster in 1910-1911 not only confirmed Mrs.

Maunder's findings with respect to the earth, but also found a similar relationship with respect to other planets. This was particularly marked in the case of Venus. If this planetary effect is real, it is something to cogitate about, but there appears to be no satisfactory explanation for such effects at the present time.

From time to time various investigators have resorted to some sort of electrical hypothesis to account for the origin of sunspots. Such an hypothesis presumes that electrical charges exist on the sun, and that the various planets are at different potentials. Since our present state of knowledge contains no information as to such electric charges, such an approach to the problem must for the moment be regarded as highly speculative. Since both gravitational attraction and electrical attraction follow the inverse-square law, any small electrical effects which might exist between the planets and the sun might well be obscured in the gravitational constant which astronomers have long derived from the well-established equations of celestial mechanics. Perhaps in some future day, when we shall have sufficient data to consider a special field of celestial electronics, we may find some basis for the origin of sunspots that could not now be apparent. This question may well be a target for tomorrow.

Chapter 11

PREDICTING SUNSPOTS

THE IMPORTANT RELATIONS between sunspots and radio communication conditions have raised a very practical problem. This is the question of how best to predict sunspot activity, months or even years in advance. If with reasonable assurance we can anticipate a degree of solar activity as measured by sunspot numbers, we can with a certain amount of confidence forecast the wave lengths and frequencies of the radio spectrum that will insure best results over a given path for a given time of day or year.

A request came in the early spring of 1946 to predict the next sunspot maximum. After considerable study of curves, graphs, heliographic latitudes and longitudes of sunspots during the past years, I ventured the prediction 1948.2 as the most probable date for maximum solar activity of the present cycle. Other predictions have independently been made, utilizing different methods that have proved to be favorites with the predictors, and give forecasts for the next maximum as 1947.6, 1948.0, 1948.3, 1948.7, 1949.5 and 1950.4. Where experts disagree it is obvious that we do not yet have sufficiently exact knowledge definitely to assign the time of the next top in the sunspot curve. It appears at the present writing that, taken as a whole, the year 1947 will show the highest sunspot number for any year of the current cycle.

Of course, how one draws the curve depends upon how one predicts the turning point. Sunspot activity can vary widely from day to day. There is a definite tendency for recurrence of sunspots with every rotation of the sun, covering an interval

of about twenty-seven days. This is due to the fact that some large sunspots may persist for more than a month at a time, and will be recounted in the return trip across the solar face as the sun rotates on its axis. Then again, even though a given sunspot as an individual may vanish, it often marks a region of most probable disturbance where new sunspots will break out, hence the tendency for an increase in sunspot numbers with each rotation of the sun every twenty-seven days. If we take the average of the daily sunspot numbers for a given year, we may plot them and find a much smoother curve than were we to attempt to plot the daily or even the monthly values. The extreme amplitude of the yearly curve will also be much lower than the extreme amplitude were we to plot monthly or daily values. The curve of yearly values probably best brings out the main cycle of the sunspot period of about eleven years, although the interval of maximum to maximum may vary widely from this period. Representation of the average yearly sunspot number from 1750 through 1946 is shown in Figure 25.

Because of the fact that there seems to be definite patterns of recurrences of sunspots at shorter intervals than a year's time, it is sometimes convenient to take quarterly averages; or, better yet, a smoother graph of sunspots showing the secondary fluctuations may be made by taking a three-months' running mean or moving average. Such a graph of three-months' moving averages from 1922 to 1946 is shown in Figure 26. It will be seen in this graph that the last maximum occurred in the middle of the year 1937. If we refer to a curve drawn from twelve-month moving averages in Figure 5 (page 57), we see that the top of the curve came in April 1937. One can readily appreciate, therefore, that in predicting sunspot maxima we must keep in mind the kind of graph for which the turning point is predicted. My prediction of 1948.2 is on the assumption of a three-month's moving average. This may be regarded as an educated guess as to where one of the secondary peaks in

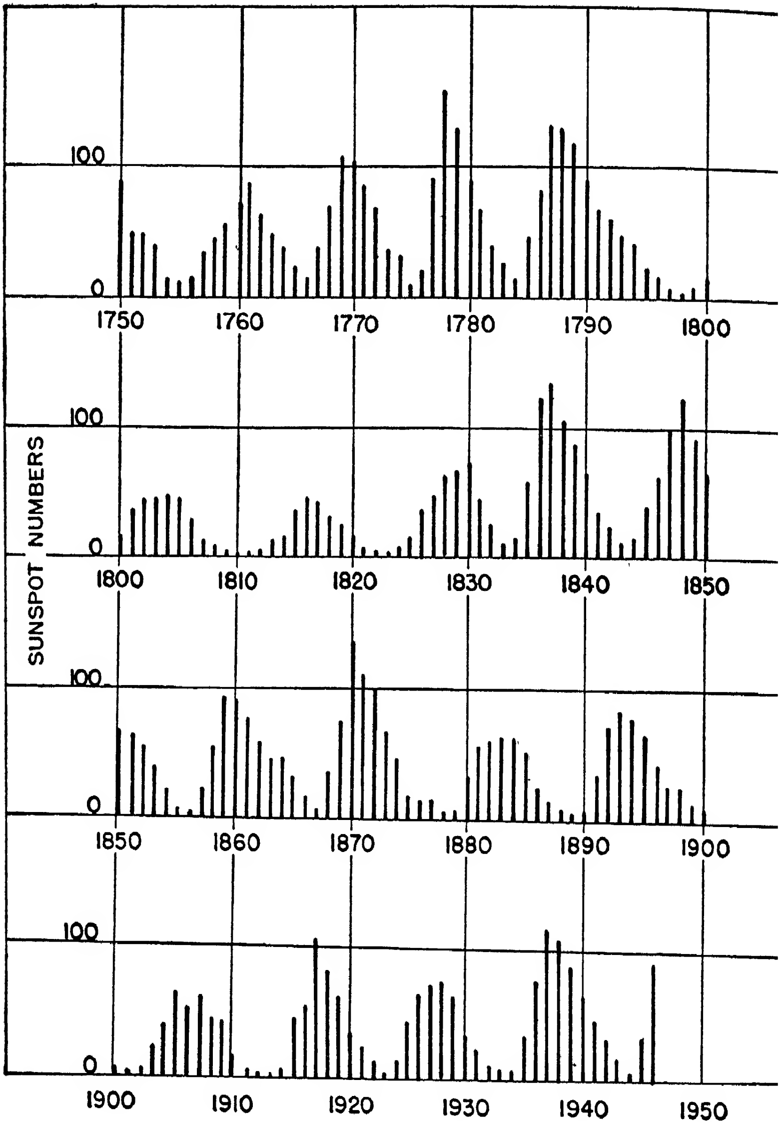


Figure 25. Sunspot numbers from the year 1750 through 1946

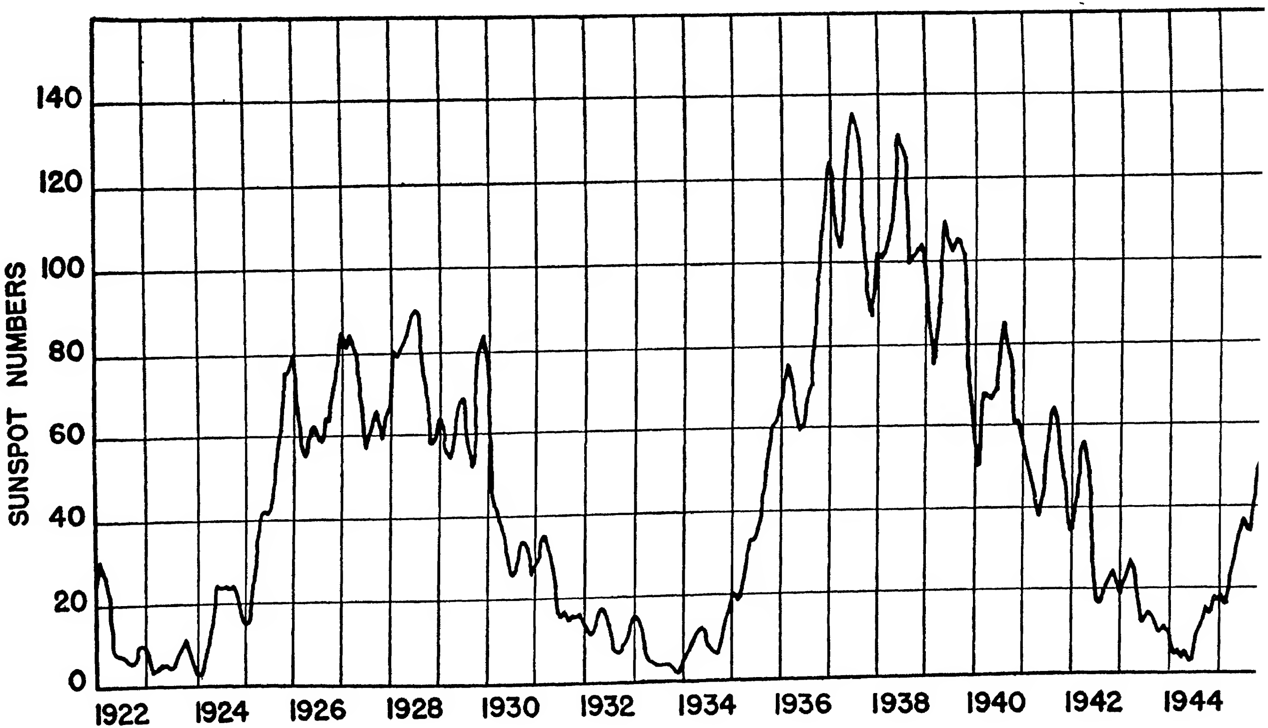


Figure 26. Three months' moving averages of sunspot numbers, 1922 through 1946

this curve may be anticipated to coincide with the major trend over the years. In this way we may hope with luck to arrive at the time for the maximum value of sunspottedness for a three-month-average curve.

Various methods have been employed by various students of sunspots in making predictions. We have shown in the previous chapter that our present knowledge cannot boast of any satisfactory theory of sunspots and their origin. Obviously, since we do not know their cause and the laws of their behavior pattern, only some empirical method based on the general pattern of recurrences can be used in making estimates of the future of the sunspot curve. Mathematicians have spent many hours in a harmonic analysis of the sunspot curve, utilizing all the data available from the beginning of reliable sunspot observations. Anyone versed in mathematics knows that any curve that one may draw, no matter how many fluctuations it may contain, can be expressed in terms of the recurrences of different periods if we take enough such periods into account. However well such a curve can be reproduced on this basis, any attempt to apply this method in forecasting the future of the curve is likely to be futile unless there are some physical bases for the periods arbitrarily chosen to reproduce the curve mathematically.

It is little wonder that many astronomers have questioned the reality of a sunspot period at all, and dismiss the question by assuming that, due to more or less random causes, the disposition of heat and energy within the sun itself is subject to vagaries in its behavior. The vortical whirls producing the sunspots on the surface of the sun in such a picture represent the uprushes of gases from inside the sun due to the accumulation of stresses that for some reason more or less periodically disturb the entire equilibrium of the sun. This theory might be called the "geyser theory," since the disturbed periods, more or less irregular, occur much as the spouting of a geyser which

gives vent at intervals under the accumulation of stresses at the base within the earth. This geyser theory of sunspots has the advantage of dismissing the question of attempting any accurate prediction of sunspots whatever.

Those scientists who still cling to the possibility that in some way the planets circulating about the sun are the fundamental cause of disturbing the sun's equilibrium still entertain a lingering hope that we can with increased knowledge improve our prediction of sunspots. The possibility of such a variety of changes in the composite effect of all the planets is so great that a very long interval of time indeed might elapse before we would have a complete repetition of a given pattern of sunspot behavior.

Those who have assumed a real physical basis back of the mathematical analyses of the sunspot curve have listed many periods from the sunspot curve that can be compounded to reproduce with fair accuracy the curve of sunspots during the last three hundred years. Among the various periods that have been thought to be real are those of eight months, eleven months, thirteen months, fifteen months, five and a half years, seven years, eight and a half years, ten years, eleven and a fraction years, also thirteen and fourteen years, eighty-nine years, and even three hundred years. Practically all agree on the existence of a period of a little in excess of eleven years.

A study of our curve on page 148 will reveal that the time between yearly maxima has varied all the way from about nine years to seventeen years. One hears much about the eleven-year sunspot period, but it must be emphasized that this eleven-year period is the average of intervals between maxima of a good many sunspot cycles. In fact the chance of predicting successfully a coming maximum on the basis of adding eleven years to the year of previous maximum is only about one in four.

The late Henry Helm Clayton, a meteorologist who was for many years an investigator of solar relations to weather

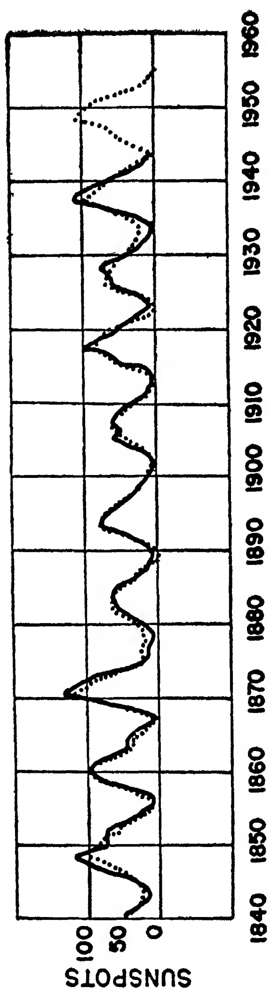


Figure 27. Predicted curve of sunspot numbers based on planetary positions, as depicted by H. H. Clayton. Dotted curve = predicted. Full-line curve = observed

phenomena, recently reconsidered the possibility of planetary effects on sunspots. Seeking out the times when a pair of planets were at their maximum distance from the sun's equator as an epoch, he utilized the mean periods of the planets in constructing a curve that shows through the years a remarkable coincidence

with the curve of sunspot numbers. The accompanying graph, Figure 27, shows his composite graph in which seven planets are involved. The full-line curve represents the actual curve of sunspot numbers, and the dotted curve the hypothetical sunspot curve based upon past solar activity and the motions of the planets. It will be noted that the dotted curve beyond 1945 represents a prediction of sunspots for the next ten years. This predicted curve shows the next sunspot peak in 1948. This is in good agreement with the predictions by others, of which mention has been made.

Dr. John Q. Stewart, of Princeton University, with the assistance of F. C. Eggleston and H. Panofsky, has recently devised a method for predicting the time of sunspot maximum and minimum, treating each rise and fall in the sunspot curve as an individual event. Dr. Stewart's method makes no assumption as to any long-term periodicities in sunspot phenomena, but rather favors the hypothesis that each rise and subsequent fall is an independent outburst. Studying these "independent outbursts," he concedes a certain tendency to a more or less definite form in the various recurrences, and from the type of form which one of these "outbursts" assumes after it is well started he has devised a formula for predicting the remaining course of a given cycle. On this basis he predicted the minimum of 1944 to be exactly in the middle of the year. This is within one tenth of a year of the actual minimum observed on the basis of our three-month moving average curve shown in Figure 26 on page 149. Dr. Stewart has communicated to me his prediction for the occurrence of the next maximum, which he places as 1948.0.

Dr. C. N. Anderson, of the Bell Telephone Laboratories, has made an extensive analysis of the sunspot curve, bearing in mind the possibility of a twenty-three-year period being the major cycle involved. Accordingly, he has drawn sunspot data with alternate eleven-year periods above and below the line

which he uses to represent the time axis. (See Figure 28.) From the analysis of his curve, he decided to adopt 22.5 years for the principal period, and concluded that other components were either fractions or multiples of a period extending over three hundred and twelve years. He also found significant periods of 17.3 and 18.4 years. On the basis of these findings, he was able to reconstruct the sunspot curve fairly accurately from 1749 to 1938, and he has projected his curve into the future to the year 2000. An inspection of his curve shows that on this basis the next maximum, which he has plotted on the underside of his zero line, would be expected to occur in 1951. Present observational evidence, however, indicates from other reasoning that the current sunspot cycle will be well past its peak by the year 1951.

Another mathematical approach to the sunspot curve was recently published by W. Gleissberg. His mathematical treatment is somewhat involved but is based on empirical laws derived from many years of sunspot data. He arrives at the conclusion that the chances are 19 to 1 that the next sunspot maximum will occur before May, 1948. This is in agreement with Waldmeier, of Zurich, who places the maximum at 1947.6. Gleissberg comes to the conclusion that solar activity at the next maximum will be extraordinarily high. This is somewhat at variance with the general pattern which has been followed in recent years.

Observation of the sunspot curve will show that there has been a tendency to alternate between sharp, high maxima and lower flat-top maxima. The sunspot maximum in 1917, for example, was sharp and high; that of 1928, definitely flatter and lower. In 1937 we again had a high-sharp peak, and if this recurrent pattern was to repeat itself, we should expect a lower, flatter top at the time of sunspot maximum in 1948. It is interesting to note that had Gleissberg's method been used for a prediction of recent sunspot numbers, the "most probable" values

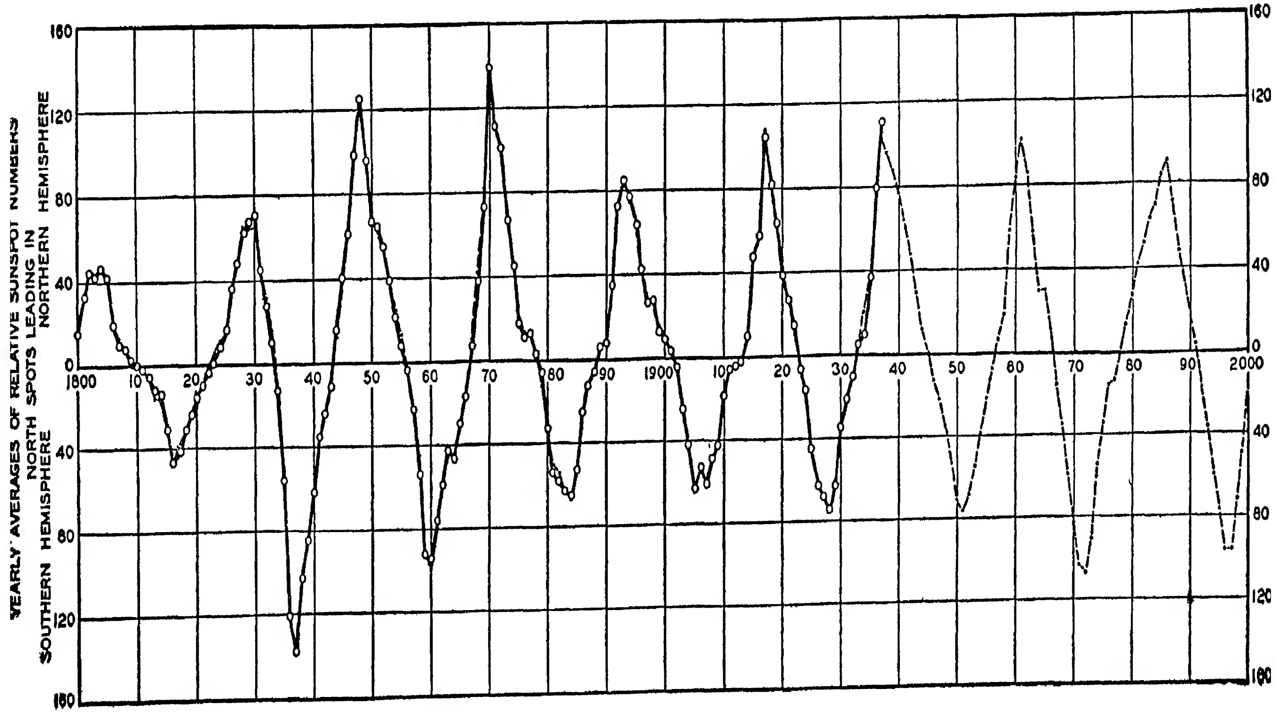


Figure 28. Sunspot cycles with predictions, after C. N. Anderson

of the sunspot number for the last two maxima would have been 191 and 161, respectively; whereas, the actual values of the smoothed curve in 1937 and in 1928 were only 119.2 and 78.1, respectively. Present indications, however, show that sunspot activity of the present cycle has already exceeded that to be expected were a flat-top to be in the making. (See Figure 29.)

The number of those who have applied various mathematical schemes in analyzing the sunspot curve and in making predictions is too great to try to represent any all-inclusive list. Enough has been said, however, to indicate that until we have some satisfactory physical picture of what makes sunspots, the question of sunspot prediction will probably remain difficult. At present only empirical methods can be used. The sun apparently is still capable of surprising us. Any approach to the empirical method generally takes into consideration the times for both minima and maxima, the rate of rise in the sunspot numbers with the beginning of each new cycle, and the rate of decline following a given maximum.

Another factor which seems to be an important one, and that helps materially in finding out where we are in a given year of the solar cycle, is to give due consideration to the latitudes of the spots that are being observed. We have remarked that at the beginning of each new solar cycle, the first outbursts occur in high latitudes on the sun in the neighborhood of 40°, either north or south of the solar equator. As the solar cycle progresses, new outbursts occur at lower latitudes progressively. At the time of maximum solar activity it is found that the latitudes of the spots are on the average in the neighborhood of 18°, either side of the solar equator. With the advance of the cycle to sunspot minimum, new spots occur nearer and nearer the solar equator, until the last spots of a given cycle are only two to five degrees from the sun's equator itself. Before the sunspots of a given cycle have finally vanished near the equator, new outbursts of the next cycle of sunspots have

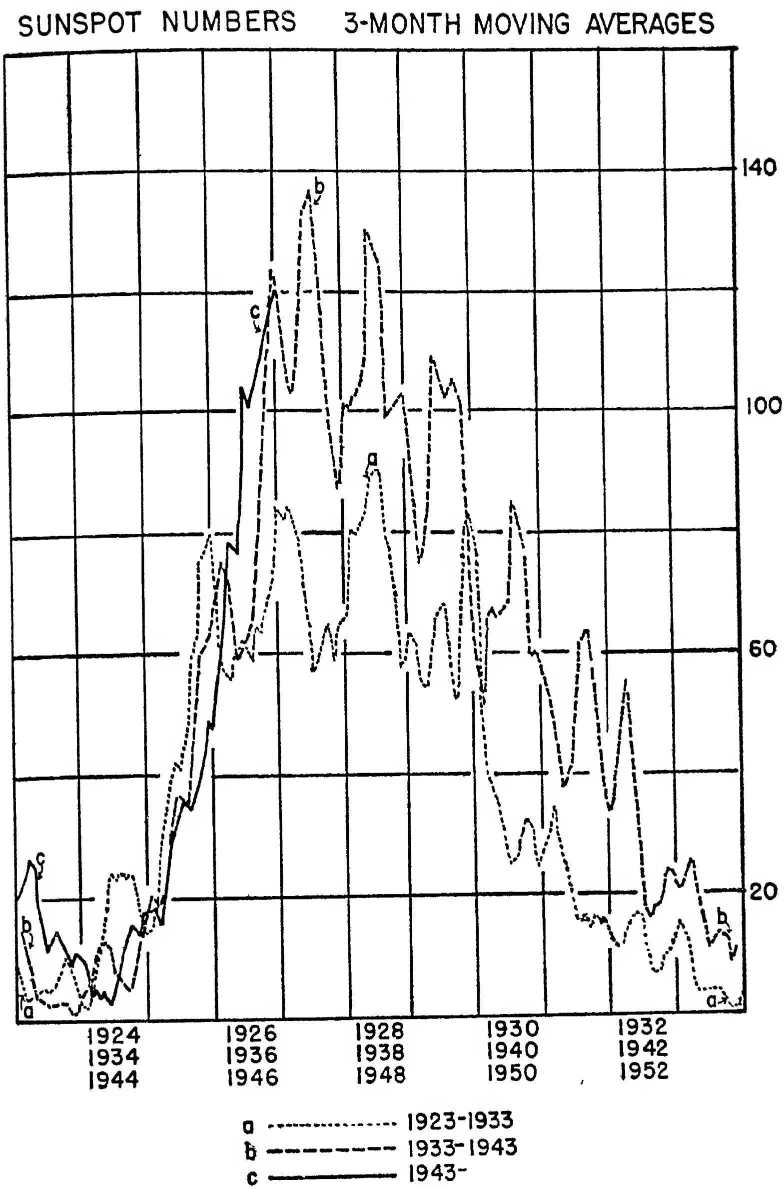


Figure 29. Formation of maximum of sunspot curve for three recent cycles

already occurred, and it is important in the study of sunspot numbers not to confuse spots of the new cycle with those of the old.

In Figure 30 is shown a plot of the average monthly latitudes of sunspots sorted out by the latitude zones in which they have occurred. A study of this chart will show that in 1934 there were two families of sunspots on the stage at the same time; those of the new cycle showing averages month by month from 30° to 20° in both the northern and southern hemispheres; whereas the old cycle spots, rapidly dwindling, occurred between zero and 10°, on the average. The last of the old cycle disappeared in 1935. The new cycle sunspots then shows outbursts in both high and middle latitudes. If we regard the next sunspot minimum that occurred in 1944, we can again trace the diminishing numbers of spots in the 1934-1944 cycle in the lower zones of latitude. It is to be noted that spots of the present sunspot cycle began as far back as 1943 in latitudes of more than 30°, either side of the solar equator. The drift of the sunspots of a given cycle in latitude is another somewhat rough indicator of when we may expect a given sunspot maximum or minimum to occur.

From the average latitude of the spots observed, as this chapter is being written, we again draw the deduction that the coming sunspot maximum may be anticipated to occur not far from the early part of 1948. Time will reveal the validity of the use of such assumptions in predicting the current maximum.

For those interested in greater details concerning various methods of sunspot predictions, attention should be called to an excellent summary of the subject in a research publication issued by the Interservice Radio Propagation Laboratory of the National Bureau of Standards at Washington. The title of the paper is "The Prediction of Solar Activity," and there is appended a bibliography of sixty-six references on the subject.

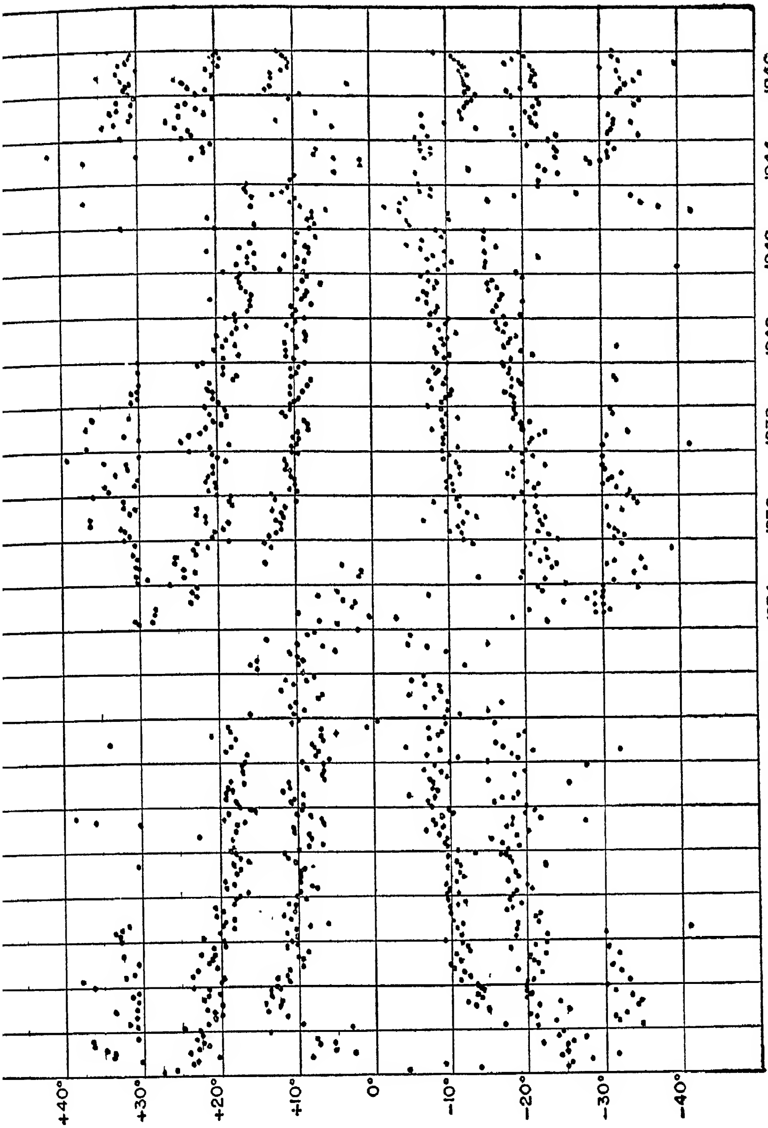


Figure 30. Locations of sunspots by zones, showing drift of latitude with progress of the solar cycle

Chapter 12

SUNSPOTS AND THE WEATHER

Do SUNSPOTS have anything to do with the weather? This is one of the questions that is invariably in everybody's mind when sunspots are mentioned. Unfortunately, the answer is not a simple one. Meteorologists who generally are concerned with the details of temperatures, barometric pressure, humidity, zonal indices, and air mass analyses feel that the many unknown factors in weather phenomena are already sufficient without adding to the forecaster's bewilderment by having to worry about the vagaries of sunspots.* Forecasting the many changes of weather to which our country, and particularly the Northeastern section of the United States, is forever subject is a difficult enough problem in itself, even when the weatherman confines himself to familiar data. Yet, in the last analysis, probably every meteorologist will agree that were it not for the heat of the sun we should have little weather to predict.

Certainly, the seasonal changes in storm tracks as well as in temperatures may be attributed fundamentally to the annual change in the position of the sun. The accompanying changes in the length of the day, and the amount of heat and radiation which a given part of the earth receives during the sunlight hours, are responsible for the differences between winter and summer weather. With the accumulation of increasing evidence of connections between solar activity and the earth, even conservative meteorologists are now conceding the possibility that changes in solar radiation may be ultimately connected with changes in weather patterns. The amount of variation in the

actual heat received by the earth as a whole throughout the solar cycle as measured at the earth's surface is relatively small. This makes it difficult, on the basis of the heat factor alone, to try to account for short-time weather changes on the basis of sunspot activity.

When one considers progressive changes in weather over the years, the meteorologist would say we are concerned with climatology rather than with meteorology. Certainly there is evidence that climates of different regions on the earth's surface have changed to a greater or lesser extent during recorded history. Anyone who has taken pains to examine climatological data knows that there have been periods of excessive rainfall and periods of excessive drought. The question of whether or not such periods are related to solar activity falls into a category of investigation that is rather different from the chores of the day-to-day forecaster.

Everyone who has strolled through forests where lumber activities have taken place has here and there stopped to observe the impressive array of rings in some stump remaining after a tree has been felled. Careful examination of a clean saw cut will show a system of ring formation of very definite pattern. Everyone knows that each tree ring marks a year's growth in the tree, and that counting the number of rings from the periphery to the heart will give a very fair estimate of the tree's age. During those years when the tree has encountered conditions unusually favorable to growth, the spacing between the adjacent rings widens. When, on account of drought or forest fires, uncongenial conditions to growth have been encountered, the spacing between the rings is unusually close.

These phenomena bring vividly to mind the results of a lifetime study of one of America's most distinguished men of science, Professor A. E. Douglass, of the University of Arizona. Professor Douglass is at once an astronomer and an archaeolo-

gist, for he has used both the methods of astronomy and the methods of archaeology in tracing the history of trees, not only through centuries but through millennia.

For many years Dr. Douglass was director of the Steward Observatory at Tucson, and later of the Tree Ring Laboratory which he founded because of his interest in the records of tree growth as an index both of climatology and of sunspot history. Professor Douglass has always been interested in growing things, and has a rare combination of analytical ability combined with the genius of a synthesizer. He has been keen to sense the interlocking evidence of several fields of science in the solution of a single problem. In roaming the Arizona forests and painstakingly counting the rings in the remaining trunks of fallen trees, he was quick to observe that periods of retarded growth frequently alternated with periods of rapid growth, and learned to become an expert in the history of trees. His discerning eye noted that in well-selected specimens there were many cases in which ten to a dozen rings separated intervals of rapid growth from intervals of retarded growth. This ten to twelve year interval suggested to the astronomer the sunspot period. Believing that the growing conditions under which trees survive might be varying with the sunspot cycle, he began an intensive study, counting tree rings by the thousands to discover whether his assumption could be justified.

As specimen after specimen of the Arizona pines, the redwoods of California, and the giant Sequoias were brought into his workshop, storage space came to be at a premium at the observatory, so the university afforded him larger quarters for the start of his Tree Ring Laboratory. The problem of analyzing spaces between rings by the thousands would be a discouraging one for a man without the persistence and scientific enthusiasm of Professor Douglass. To cope with the problem, he devised a novel scheme for analyzing the periods in the growth of trees. By means of an elaborate optical contrivance

he could take the tree-ring pattern of a single specimen or a dozen specimens, and in a relatively short time discover intervals of eleven years, seven years, twenty-three years, and longer, to which variations in tree growth had definitely responded. In this country he found the sunspot cycle nearly always split into two maxima. From examination of trees in German forests, he found that a single maximum was more common but not universal.

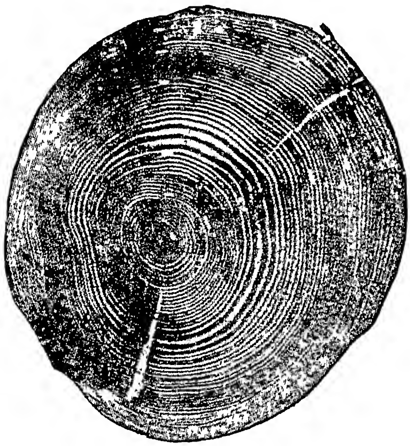


Figure 31. Tree rings register solar cycles through the centuries. (*After* A. E. Douglass.)

While there were wide variations in the growth patterns of trees taken from different forests, there was a similarity in the space intervals between periods of most rapid growth throughout the whole southwestern territory. (See Figure 31.) As his analysis progressed, it was more and more evident that the eleven-year sunspot period, and other periods related to it, were reflected in this biological survey.

It was evident that in the tree trunks there were indelibly recorded conditions of weather and climate long before mankind ever thought of establishing weather bureaus or meteoro-

logical stations. Where tree rings were crowded close together year after year, it was obvious that there had been great droughts in the Southwest that had retarded growth. Here and there Dr. Douglass caught the records of vast forest fires that had swept the primeval woodlands and suddenly dwarfed the growth. But he learned to make allowances for these catastrophic interruptions whose telltale patterns were clearly recognized.

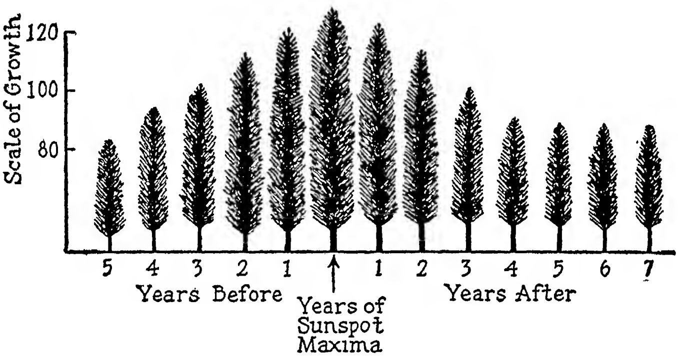


Figure 32. Growth of trees increases with sunspots. (From *Sunspots and Their Effects.*)

The idea that the analysis of tree rings, betraying periods of drought and rainfall over centuries, might ultimately lead to the possibility of long-range weather forecasting was a persistent stimulus to the worth-whileness of his researches. Furthermore, if the tree-ring patterns reflected the solar cycle, was there not here a definite indication of the intimate association of sunspots and biological behavior—at least so far as tree growth was concerned? In order to establish definite connections with the sunspot variations, it was obviously necessary that he know not only the age of the tree, but also the identical year corresponding to any particular ring. So Professor Douglass had to build up a tree chronology that would carry from the present far back through the centuries.

Beginning with the outermost ring of a tree just cut down, and counting toward the heart of the trunk, the ring pattern could be definitely identified with the calendar. With sufficiently old trees, the time spacing of special ring patterns could be carried over from living trees to more ancient specimens whose date of felling was unknown. The persistence of the ring pattern definitely showed cross-dating, or "cross-identification," as Dr. Douglass calls it, and by such a scheme he was able to carry back the record of the tree rings for more than three thousand years. In a succession of trees in Arizona he has an actual record of nineteen hundred years; and in the case of the Sequoias, of thirty-two hundred years.

At times there would be gaps in his chronological sequence. There seemed to be no specimens available which would connect the ancient with the more modern period. Somewhere, thought Professor Douglass, in the ruins of some ancient pueblo of the Southwest, there must lie timbers cut from trees of just the years that are required to bridge the gaps.

But where to go for such specimens was a problem. Professor Douglass' contributions to chronology had already brought him into high esteem among archaeologists, and archaeology now lent its hand to help in the solution of the problem.

Scattered among the ruins of the ancient Hopi villages were specimens and fragments of pottery of all sorts. Archaeologists are more or less familiar with the evolution of pottery patterns. So Professor Douglass thought that if he could learn to read the chronology of pottery, he might gain information as to the particular ceramic pattern that must have evolved during the years of his gaps in the tree-ring sequence. Then it would be only a question of letting fragments of such pottery guide him to the proper sites of the early pueblos, and he would have a fair chance of unearthing timbers there that would show tree-ring patterns for those periods where data were lacking.

So Professor Douglass mastered the archaeological art so far as pottery was concerned, and then proceeded on his romantic search. With eager delight he at last found a pueblo wherein lay fragments of the type of pottery sought. True to his expectations, he found there the ancient timbers that concealed the coveted chronology. Within those old timbers were the tree-ring patterns that overlapped both sides of the gap that had caused him so much anxiety. Thus, after long patient years, this veteran of science was able to complete his chronological cycles. For the happy ending to one of the most fascinating chapters in science, the Research Corporation bestowed upon Dr. Douglass its prize award of $2500.

Dr. Douglass' constant searches for new specimens have taken him all over the world. For more ancient relics he has examined Egyptian sarcophagi, there to find cycles of rainfall and drought dating back to the Pharaohs.

During his studies, one thing bothered our astronomer-archaeologist most exasperatingly, and that was that in the tree rings that he had dated between 1645 and 1715, he found very little indication of the eleven-year sunspot cycle that was supposed to have had maxima during that interval.

One day early in 1922 Professor Douglass' morning mail brought a letter from Professor Maunder, of the Royal Observatory in Greenwich, England. In this letter Professor Maunder told Professor Douglass that he had been searching into early records of sunspot observations with some surprising results. This search of the English astronomer had revealed that a great dearth of sunspots had been observed during the entire period from 1645 to 1715. Maunder knew nothing of Douglass' difficulties, but merely wished to convey to him the information of this remarkable discovery in sunspot data. He ventured to remark to the Arizona scientist that if there were any real connection between his tree-growth theory and the sunspot cycle, he should have found evidence lacking as to

sunspots in his tree-ring records between 1645 and 1715. Thus we see how a strange failure of sunspots to appear during the middle of the seventeenth century actually corroborated Douglass' findings at a time when he had nearly given up the idea of the connection between sunspots and tree rings on account of an apparently unexplainable discrepancy.

However skeptical some scientists may have been in regard to Professor Douglass' theory of sunspots and tree growth during the early days of his investigation, there are few well-informed scientists today who have not accepted the connection. The obvious inference of all these years is that since tree growth responds readily to rainfall and drought, periods of sunspots have been related to periods of abundant or deficient moisture in the great Southwest.

Many investigators have endeavored to trace records of rainfall in recent years with numbers of sunspots. The result has left many inconsistencies. The problem is most baffling. Is it possible that other factors than moisture alone have entered into the rate of growth of trees and all other growing things? With years of equal precipitation is it possible that more sunshine or more ultraviolet light in the solar radiation may have been an added stimulation to growth? It would appear reasonable that a tree sufficiently sensitive to have recorded each year's growth in its ring pattern should have unconsciously taken into account every factor favorable and unfavorable to its continued existence.

In the painstaking work of Professor Douglass we may assume with confidence that the sunspot cycle and long-period changes in weather or climate have been sufficiently well-established to command the respect of the most conservative scientist. The question, however, whether day-to-day changes in weather may be in any way directly related to sunspot phenomena is still a matter of discussion. Various workers in the field of solar terrestrial relationships have at times pre-

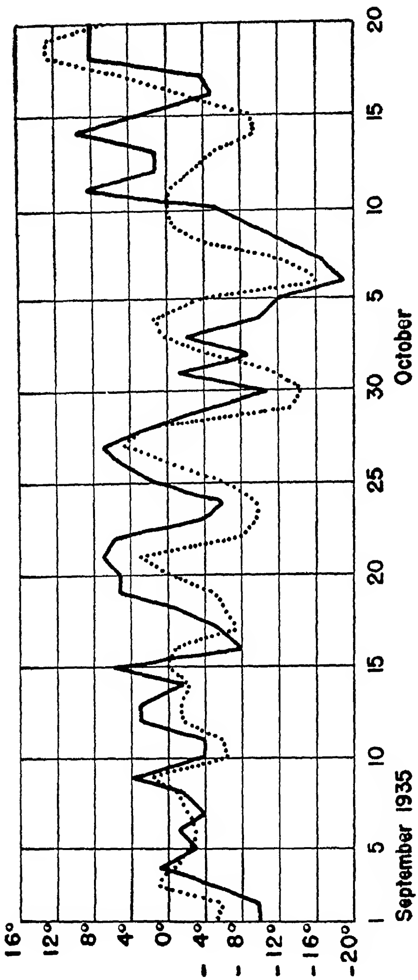


Figure 33. Prediction of temperature departures in Washington, D. C., by C. G. Abbot

sented much evidence to support such a relation. Then, as is so often the case, the pattern changes, and we have inconsistencies to dampen the enthusiasm of the most ardent worker.

Dr. Charles G. Abbot, of the Smithsonian Institution, whose painstaking work in maintaining continuous measurements of

solar radiation have already been mentioned, is a firm believer in the connection between solar radiation and the weather, and has published voluminous papers giving observational evidence in support of his theory. On the basis of solar activity, Dr. Abbot has attempted to make weather predictions days and even months in advance.

As an example of such predictions we may call attention to Figure 33, in which are represented Dr. Abbot's predictions for temperature departures from normal for the months of September and October in 1935. Making a careful comparison of the number of flocculi appearing on the sun that corresponded to certain departures in temperatures, Dr. Abbot used these flocculi as an indicator of solar change from which he drew the dotted curve in Figure 33 to represent corresponding changes in temperature that could be anticipated during the months of September and October in 1935. Thus, in a sense, the dotted-line curve may be called temperature predictions for this interval. Since his findings indicate that temperature changes are of importance until at least fourteen days after the corresponding solar changes have been observed, Dr. Abbot has in reality represented predicted temperatures for ten days in advance. The solid-line curve shows the temperatures that were actually observed during the same period. The average difference between the predicted and the observed daily temperatures proved to be somewhat less than five degrees Fahrenheit. Furthermore, on the basis of solar periods and their association with rainfall, Dr. Abbot has ventured to predict for years in advance periods of excessive precipitation and periods of relative drought. Such a curve is represented in Figure 34, where the dotted line represents the predicted rainfall at Peoria, Illinois, for 1934, and the full-line curve the actual rainfall during the same interval.

Another ardent worker in the field of weather and sunspots was Mr. H. H. Clayton, whose name has already been mentioned

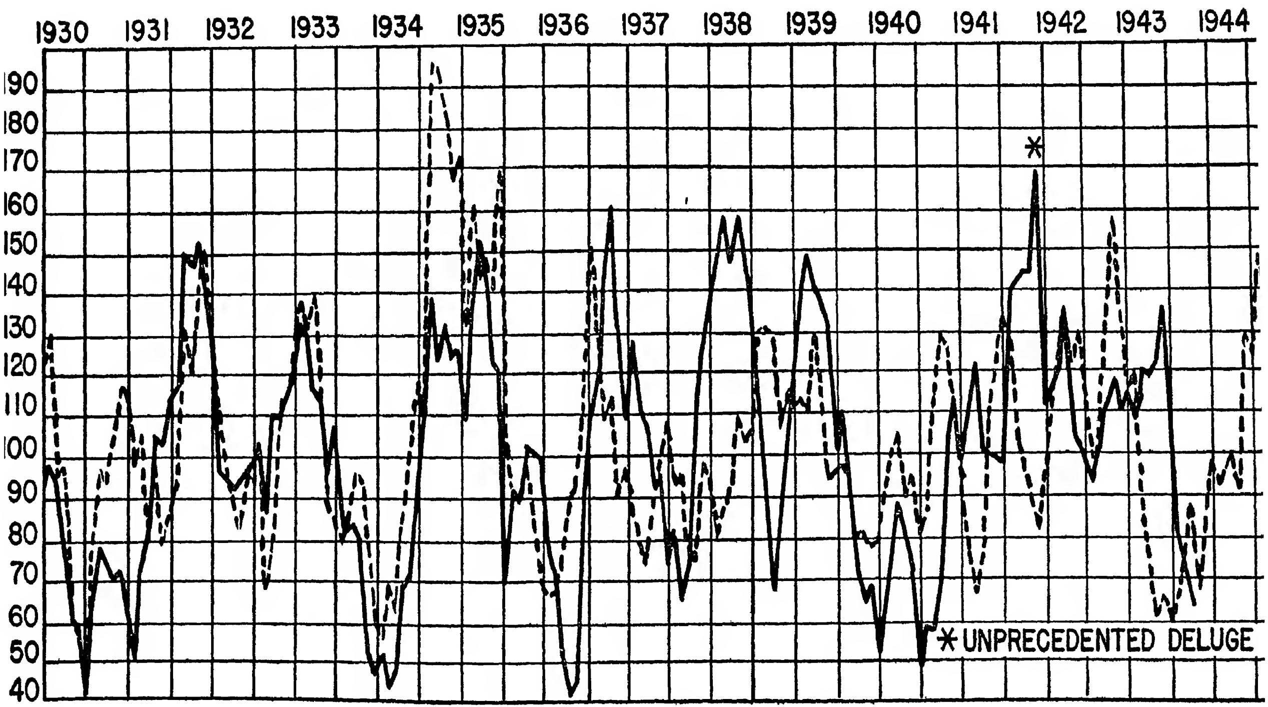


Figure 34. Precipitation at Peoria, Illinois, 1930-1934, as predicted by Dr. C. G. Abbot (dotted line), and as actually observed (solid line

in the chapter on the prediction of sunspots. Mr. Clayton has long been known as a meteorologist who has a comprehensive view of weather changes on a global scale. Some of his more recent findings have exhibited striking relations between tem-

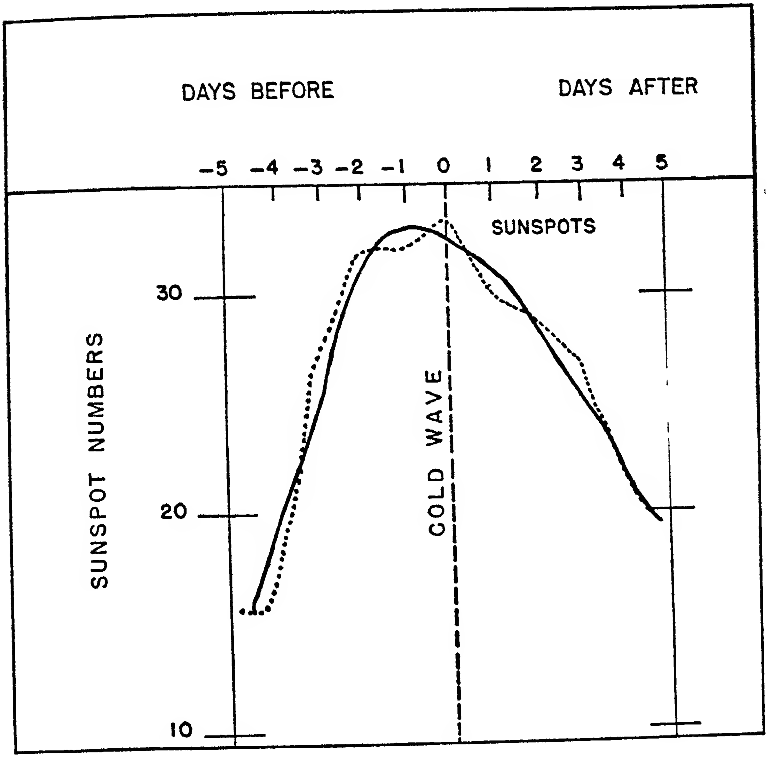


Figure 35. Average sunspot number preceding and following the coldest day in each cold wave at Minneapolis, winter of 1942-1943, by H. H. Clayton

perature changes and sunspots. Based on the winter of 1942-1943, there is shown in Figure 35 a representation of the number of sunspots which he has found preceding and following the coldest day in each cold wave experienced at Minneapolis, Minnesota. In Figure 36 there are represented the progressive

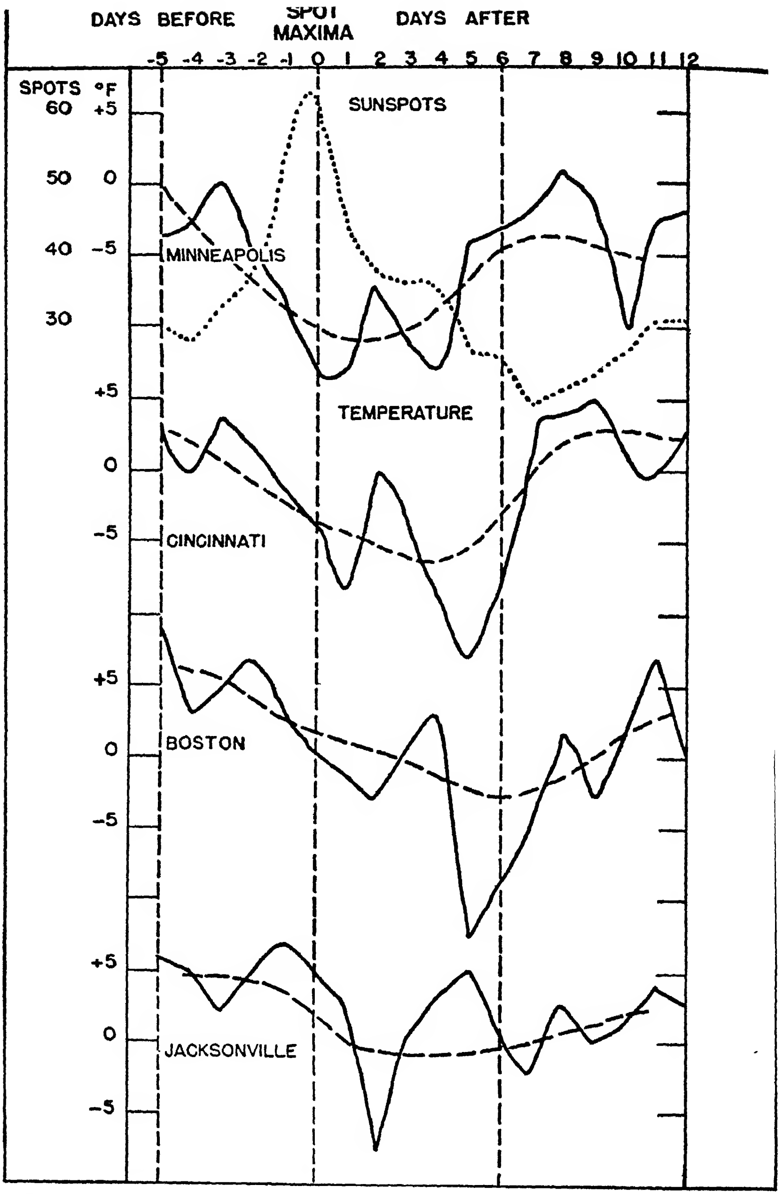


Figure 36. Mean temperatures at Minneapolis, Cincinnati, Boston, and Jacksonville, preceding and following marked maxima in sunspots, winter of 1942-1943, by H. H. Clayton

changes in temperature for Minneapolis, Cincinnati, Boston, and Jacksonville, together with the curve of sunspot activity before and after marked maxima of sunspots. From this graph it will be noted that, five days after a high degree of solar activity, the lowest temperatures occur in Cincinnati and in Boston. These graphs are again based on the observations of a single winter of 1942-1943. Critics of Mr. Clayton will emphasize that the data of a single season are far too meager for generalizing conclusions. Mr. Clayton would probably have been the first to acknowledge the limitations of such an exhibit, yet the comparison is so striking as to command attention.

Investigating a much wider range of material extending over many years and wide areas of the globe, Mr. Clayton established a much broader basis for such fundamental relations between weather and sunspots than these single exhibits would indicate, striking as the latter may be. Looking at the weather on a world-wide scale, he not only found that pressures seesaw from one region to another, as meteorologists generally recognize, but he also noted that the way in which they oscillate depends upon sunspots. To complicate the picture, he found that there is an opposite trend over the oceans and continents in summer as compared with winter, and that the trend is very different in the equatorial regions from what it is in the extratropical belts. In the equatorial region, the temperatures are distinctly lower during sunspot maxima and higher at sunspot minima. The same is true in the north and south temperate zones, but in the arid subtropical regions the temperature actually averages a little higher around sunspot maximum than around a sunspot minimum.

Mr. Clayton examined the snowfall records at Blue Hill Observatory, at Milton, Massachusetts, and found 40 per cent more snow at sunspot maximum than at sunspot minimum. He traced the ice records in the Arctic and Antarctic and found two to three times as many icebergs at sunspot maximum as

compared with sunspot minimum. This corroborates the findings of other investigators who have come to the conclusion that temperatures, at least in the temperate zones, are colder on the average when sunspots are most numerous.

From a careful study of precipitation records selected over the whole globe, Mr. Clayton mapped the world into regions which show greater rainfall when sunspots are most numerous, and regions where rainfall is actually deficient at sunspot

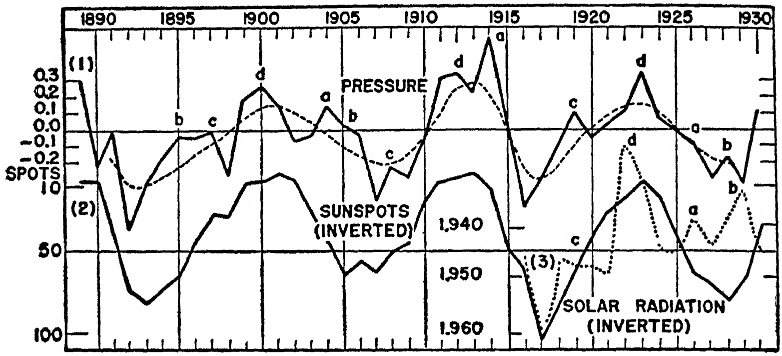


Figure 37. Comparison of mean pressures in the tropics with sunspots, as represented by H. H. Clayton

maxima. While the North Atlantic Ocean shows 10 per cent to 20 per cent more precipitation in years of greater sunspots, the eastern half of the United States is in the region where the rainfall is actually less during maximum activity on the sun. South America, Africa, India, and Australia all show again 10 per cent to 20 per cent more rainfall during sunspot maxima than during sunspot minima.

Everyone knows that changes in weather accompany the fall and rise of barometric pressure; warmer weather, in general, accompanies low barometric pressure. Clear, colder air follows, with a subsequent rise in the barometer. These local changes must, in the long run, be influenced by the distribution of

pressure over the globe. Mr. Clayton has examined the changes in distribution of atmospheric pressure over the globe, and compared them with sunspot periods. In Figure 37, taken from one of his more recent publications appearing in the "Bulletin of the American Meteorological Society," he shows a remarkable correspondence between pressure variations in the tropics as compared with sunspots.

From his survey of world weather, Clayton came to the conclusion that at sunspot maximum the atmospheric pressure is less at the equator than it is during the years when sunspots are infrequent. But this area of lessened atmospheric pressure at the equator is compensated by a zone of greater pressure at sunspot maximum than at sunspot minimum in the northern hemisphere. Any wholesale change in the distribution of atmospheric pressure, or of barometer readings over the globe, which follows the sunspot cycle must ultimately affect the number, intensity, and nature of the storm tracks over the United States or other typical regions of the globe.

Some years ago Professor Kullmer of Syracuse University investigated the tracks of storms over the United States during the years when sunspots were in evidence, as compared to the years when sunspots were lacking. On the basis of five solar cycles he found that there appears to be a shift in the storm tracks of the United States which corresponds very much to the shift in the location of sunspots on the surface of the sun. Furthermore, by examining years of solar and meteorological data, he has found on the average 40 per cent more storms passing over the fundamental storm track of North America during sunspot maxima than passed over this same region during years of sunspot minima. He based his studies on records extending from 1883 to 1913.

Many investigations have been made of the relationship between sunspots and tropical hurricanes on the earth. R. Wolf, who was one of the earliest investigators of sunspots, has

shown that during years of maximum sunspots there have been on the average six to eight violent hurricanes per year, while the average number during sunspot minimum is only one or two per year. More than three times as many hurricanes have visited the Bay of Bengal and the Arabian Sea during the years of sunspots. The South Indian Ocean, in the same period, showed an increase of 65 per cent in the number of such hurricanes. Reverse conditions, however, were indicated for the South Pacific Ocean, where the number of tropical hurricanes was twice as many during the years of few sunspots as during the years of many sunspots. Other investigations have indicated that as the sunspot cycle progresses, the longitude of the West Indian hurricanes has drifted from fifty-nine degrees west to that of eighty-eight degrees west.

All of this shows that weather is a highly complex phenomenon which depends upon turbulent air currents traveling in different directions, influenced by continents and oceans, equatorial heat, and the arctic cold. To upset the balance of one of these regions may change the character and sequence of any of these phenomena in any of the other regions.

Mr. Clayton believed that all our weather is the result of progressive wavelike movements of certain disturbed areas originating in different parts of the world. He found that during each cycle of change in solar activity, the centers of high barometric pressure move from high latitudes to low latitudes and back again. The speed with which these waves progress appears to be inversely proportional to the length of the period of oscillation. The oscillation of these pressure areas he believed to be largely responsible for the complicated weather changes that are associated with sunspots. With the high intensity of a sunspot maximum, such as was experienced in 1917 and 1937, the North Atlantic high-pressure area migrates to the latitude of Greenland. The tardiness of its return to its normal position, Mr. Clayton believed, accounts for the

reversal in phase which is often experienced in meteorological data at a given place, as compared with sunspot data.

This reversal in phase with respect to the sunspot period has confused many investigators, and has been the cause of much discouragement to those who had hoped to find relations between weather and the sunspot period. This reversal also makes clear why it is so unsatisfactory to study such periodicities by ordinary methods. On the other hand, this explanation may afford new hope of ultimately finding what connections may exist between sunspot activity and weather changes that in the end may lead to making long-range weather forecasts profitable.

This meteorologist found much in common in the behavior of the weather in widely separated parts of the earth, as, for example, in the central United States and in Australia. Changes in rainfall in central North America show a striking similarity to changes in precipitation in central South America. Changes in the barometer in San Diego act very much as they do in Buenos Aires. In this respect Ceylon varies in an opposite manner to Santiago, Chile. This distinguished investigator noted that there would be several years when the differences in barometric pressure between the equatorial region and the north temperate zone became greater than normal, and then several years later a period would follow when the pressure differences became less than normal. The shifting of these centers of action appeared to him to be definitely associated with sunspots. His conclusions are based on so large an amount of data, and upon such a wide experience in meteorology, that no one interested in weather and weather prediction can overlook the important contributions which Mr. Clayton made.

Chapter 13

SUNSPOTS, WEATHER, AND LIVING THINGS

We have seen in the previous chapter how through the years a rather remarkable relationship was found between the growth of trees and the sunspot cycle. This is probably the outstanding demonstration of any biological effect as correlated with solar activity. We have also seen that, complex as the problem is, there is growing evidence for a relation between sunspots and weather. The question as to whether sunspots, through a subsequent chain of events, influence the behavior of living things on the earth is always an intriguing one. However, in our present state of knowledge, any discussion of this subject must still be regarded as highly speculative.

There is, of course, no contention that weather is basically associated with agriculture. Seedtime and harvest have persisted in logical sequence through the ages, with the changing seasons brought about by well-understood movements of the sun. Historians, archaeologists, and climatologists have long recognized certain major cycles in civilization which undoubtedly have been associated with changes in climate. The English scientist, C. E. P. Brooks, in his *Climate Through The Ages,* and Dr. Ellsworth Huntington, of Yale, author of many books on the subject, have been constant students of the effect of weather and climate on man and his civilization. Some of these cycles of change have often been associated with either the sunspot cycle, or with longer intervals that are multiples of the eleven-year period. As far back as 1891, E. Brückner called attention to certain cycles in wheat harvests, wine making, the freezing and thawing of rivers, the water levels in lakes, and in

other natural concurrences that seemed to follow a period of about thirty-five years.

Whether or not shorter cycles that more nearly correspond to the eleven-year sunspot cycle are reflected in biological phenomena has been a matter of much concern to many investigators. Dr. Abbot has called attention to cycles which have been found to exist in the plentifulness of cod and mackerel that show a rough correspondence to the sunspot cycle. Utilizing the records of the Hudson's Bay Company, remarkable variations have been found in the number of pelts brought to market from the fox, the lynx, and the rabbit, varying in a period of from nine to eleven years' duration. From 1850 to 1900 nearly every peak in the number of rabbit pelts delivered corresponded quite closely to a minimum in the number of sunspots.

If sunspots have anything to do with rabbit population, one might wonder why rabbits appear most numerous near sunspot minima and most scarce near sunspot maxima, while tree growth seems to be favored by sunspots. Perhaps one might facetiously reason that trappers, stimulated by solar activity, have been more energetic in depopulating the rabbit world during the years of sunspot maxima! Equally well, one might reason that other animals, which are natural enemies of the little four-footed creatures, thrive best when sunspots are most numerous. The natural life cycle of the animal, together with the character of the food which it eats and its coefficient of self-preservation and self-propagation, are other factors that should perhaps enter the picture.

One does not, of course, need to argue in these enlightened days that there is a close relationship between the health-giving rays of sunshine and the welfare of the individual of any species. The small variations which have been found in solar radiation, however, leave one scanty data for seriously connecting such changes in the heat of the sun as occur from one sunspot

cycle to the next with any consequential change in biological behavior patterns.

Of course it is possible that there may be some more subtle changes in the character of solar radiation between sunspot minima and sunspot maxima than show up on any pyrheliometer measurements of the sun's heat. The question of the quality of sunshine as well as its quantity is a matter for consideration. As was mentioned in the chapter on "Metering Sunlight," we have seen that from radio investigations there is good reason for believing that the amount of ultraviolet radiation in sunshine varies as much as 100 per cent between the times of sunspot maxima and sunspot minima. The evidence which supports this, however, is concerned with the radiation falling on the top of the atmosphere where radio waves are reflected. As is well known, most of this ultraviolet light is absorbed in the lower atmosphere of the earth before it ever reaches the surface upon which life flourishes.

We do know that the absorption of this ultraviolet light creates a layer of ozone that occupies a region extending from some eighteen miles to twenty-five miles above the earth's surface. We should emphasize that if all of this ozone in the high tenuous upper air were reduced to normal conditions of atmospheric pressure and temperature at the earth's surface, it would form a layer scarcely more than two millimeters, or somewhat less than one tenth of an inch, in thickness. There is good evidence to believe that the thickness of this ozone layer varies with sunspots, and hence we may reason that the amount of ultraviolet light filtering through this ozone layer and arriving at the earth's surface varies in amount from year to year. It may well be for this reason that the sun bathers who adorn our beaches in summer time burn or tan so much more quickly in some seasons than in others. How effective these changes in ultraviolet light may be on vegetation or in promoting or retarding other biological phenomena we do not know.

Dr. Ellsworth Huntington, in his book, *Mainsprings of Civilization,* devotes considerable space to the physiological consequences that may result from the cycle in the ozone change which he adopts as of nine and two thirds years' duration. This he based upon certain European measurements made between 1877 and 1907. Hygienists recognize certain beneficial qualities in sunshine which so far do not seem to have been equalled in any artificial source of ultraviolet radiation.

The effect of radiation upon biological phenomena is a relatively new subject. It has long been recognized that ultraviolet light plays an important part in the creation of vitamin D in plants and animals. A deficiency of vitamin D inevitably leads to rickets. Solar therapists have for many years prescribed sunshine in such deficiency cases. It has been found that alfalfa grown in Arizona and cured in bright sunshine developed antirachitic powers which could not be found in the same plant cured in darkness.

Some plants are highly sensitive to light of very short wave lengths. Ultraviolet light from artificial sources is a powerful radiation. Fortunately for us, nature has given us a protective screen in the existence of the ozone layer. The small amount of ultraviolet radiation which this screening layer passes is probably that best adapted to the present state of living things on the earth's surface. It is certain that were the ozone layer half its present thickness, the resultant radiation which reaches the earth would be detrimental to life, if not fatal. Experiments made with the tomato plant have shown that its sensitive leaves are seriously injured by an undue exposure to an ultraviolet health lamp. Under such treatment the plant inevitably shrivels and dies. There is some accumulating evidence that the secretions of our endocrine glands, so essential to our well-being, are affected by varying amounts of ultraviolet radiation.

One of the most interesting experiments relative to the effect of ultraviolet radiation and the performance of glands was once

made on a pair of monkeys in the London Zoo. It appears that the pair were apparently normal in every respect, but the usual felicitations that would be normally expected between two members of the opposite sex were quite lacking. Scientists suggested that here was an unusual opportunity for experimenting with ultraviolet radiation. The pair were given carefully dosed exposures to ultraviolet light. The scientists watched for results. The results were indeed forthcoming. Not only was mating consummated but the little lady involved soon produced both twins and triplets. The idea that secretion of the ductless glands may be stimulated or controlled by the radiation of ultraviolet rays appeared to be substantiated. The result of this experiment suggested many possibilities for further investigation.

Many investigators have been concerned with the more or less definite periodicities found to exist in the recurrences of well-known epidemics. Dr. William F. Petersen, of Chicago, who is known for his many investigations of the effect of weather on physiological responses, has given serious consideration to the possibility that periodicities in infectious diseases may be dependent upon cycles in cosmic phenomena.

Dr. Petersen has called attention to the simultaneous occurrences of spasms among patients subject to cardiovascular disturbances, even when such patients are located in widely separated hospitals. Furthermore, he has associated such simultaneous pathological conditions with atmospheric disturbances incident to the approach of meteorological cold fronts.

Various investigations have been made in years past, notably by Dr. Dessauer, of Frankfurt-am-Main, and by Dr. Yaglou, of the Harvard School of Public Health, in an endeavor to relate physiological behavior to the positive and negative ions in the air. The results of such investigations have so far been conflicting and are far from convincing. Searching for some variable in the atmosphere not directly indicated by the barometer, the

thermometer, or the hygrometer, Dr. Manfred Curry, an American physician, together with his associates at the Bioclimatic Institute in Munich, presents evidence to show a close correlation between spasmodic reactions in well-typed patients with changes in ozone acting with other oxidizing gases of the atmosphere. Although the ozone content of the normal atmosphere is small, meterologists have long recognized a maximum of ozone near the threshold of a cold front, and therefore generally accompanied in the North Temperate Zones with northerly winds. There is reason to believe that the amount of ozone in the upper atmosphere may be variable with the sunspot cycles. Should the work of Dr. Curry be substantiated, we may have a new element to consider in the question of the relation of biological response to the sunspot cycle. Unfortunately, at the present writing, Dr. Curry's researches are not yet available in English, but occupy two volumes entitled *Bioklimatik,* published by the American Bioclimatic Research Institute, Riederau/Ammersee, Munich, 1946.

In a conference on cycles, held some years ago under the auspices of the Carnegie Institution of Washington, periodicities of many widely divergent fields were brought to light. In this connection, Dr. William Charles White called attention not only to seasonal relations to the onset of infectious diseases, such as are exhibited in Rocky Mountain spotted fever and pulmonary tuberculosis, but pointed out a ten-year recurrence of epidemics of meningitis, a seven-year period in diphtheria and influenza. In this connection Dr. White remarked, "We have much evidence which relates diseases in both man and animals to certain well-known cycles in nature. I think we have never yet in the study of disease cycles swung out toward their relation to the great cycles of nature, such as those occurring in the great cosmic cycles, or even in relation to the sunspots in the sun cycles. We have, however, very definite evidence of the relation in such a disease as rickets to the influence of various wave

lengths of the sun and its emanations have to a definite chemical substance known as sitosterol. These emanations from the sun and other luminous bodies at least occur in cycles of intensities, but so far as I know little study has been given to this phase of the subject, and very little study has been given to the seasonal occurrence of such a disease as rickets." Since this statement of Dr. White, more and more attention has been given to the study of these recurrences in pathological phenomena, particularly as concerns meteorological changes and human responses. Actuaries such as Walter G. Bowerman, of the New York Life Insurance Company, have made extensive studies of vital statistics from such a viewpoint. Dr. William F. Petersen, whom we have just mentioned, and Dr. C. A. Mills of the University of Cincinnati, author of *Medical Climatology* and *Climate Makes the Man,* have made notable contributions to this field from a medical viewpoint.

One should be cautious and not become over-enthusiastic in hoping to find intimate relations between variations in the public health and the sunspot cycle. Only by the most exacting scientific methods can we hope to substantiate any hypothesis which our creative imagination may engender. Perhaps if one hypothesis in a hundred should prove fruitful in such fields, we should feel ourselves sufficiently rewarded. On the other hand, not to follow up promising theories even to the point of futile conclusions may sometimes eliminate our chances of success.

In this connection, it may be worth while to point out that a natural period, or cycle, in one class of phenomena may be indirectly related to a basic natural cycle of a very definite period through an intermediary third factor. Let us take, for example, an astronomical illustration. For this purpose, consider the interval between succeeding oppositions of the planet Mars. This is known as the synodic period and for Mars is 2.14 years. This is the interval that elapses from the time when Mars is on the opposite side of the Earth from the sun, until the planet is

exactly opposite the sun again. The planet at this time becomes what is technically known as an "evening star." Now the planet Mars revolves about the sun in a period of 1.88 years. To the casual observer there would appear to be no relationship between the time it takes the planet to revolve around the sun and the time one must wait until Mars is "evening star" again. When one takes into consideration, however, the motion of the earth as a very important part in repeating this particular configuration of opposition, the relationship between the period of revolution of Mars around the sun and the synodic period becomes evident. Both the earth and Mars are revolving about the sun in nearly concentric orbits. The earth, being nearer the sun, revolves faster, so that it completes its cycle in exactly one year. A little calculation will show that the time it takes the earth to recapture its position with the planet Mars may be expressed as follows: $1/S = 1/E - 1/P$. Where P equals the period of revolution of the planet, E equals the period of revolution of the earth (one year), and S equals the synodic period, that is, the interval between successive oppositions. If we substitute the known values, $P = 1.88$; $E = 1$; we shall find that $S = 2.14$, the interval between oppositions.

Using this analogy in the case of the well-known periodicity of seven years for the recurrence of diphtheria, we can show how the solar cycle of eleven years might be involved were we to assume an unknown period in the life cycle of some infectious microorganism upon which the recurrent interval of diphtheria depends. From the formula stated above we may deduce the hypothetical life cycle supposed for the intermediary microorganism. In this case, the observed period of seven years would correspond to our synodic interval in the example of the planet Mars. We may take eleven years as the average period of sunspots. This will be the value of P in our formula above. If we substitute these numerical values, we find the value of E to be the period of the hypothetical life cycle of our unknown

organism. In this case we find that $E = 4.3$ years. We should be led, therefore, on this hypothesis, to search for a period of 4.3 years in the life cycle of our assumed microorganism. Please be assured that this is not an attempt to say that the microorganism responsible for the diphtheria is related to sunspots, or that diphtheria depends upon an hypothetical organism with a life cycle of 4.3 years. The illustration, however, is important, in that it represents a method of treatment of data where more than two related cycles are involved. The example will serve to emphasize that cycles which apparently show no direct correspondence with the solar cycle are not for that reason necessarily unrelated to it.

However speculative it may appear to suppose that life, health, and behavior patterns may be dependent upon cosmic factors beyond our control, it is not altogether futile to get outside ourselves and take a look at life from the cosmic viewpoint. We may look upon all life on the earth as an aggregate of conglomerations of a curious substance we call protoplasm. From the cosmic viewpoint, life exists as tiny organisms in a microscopic film at the surface of the small planet on which we live. It exists only because of the presence of moisture, water, oxygen, and other necessary chemicals. It continues to survive only because of the amount and quality of the light and heat radiated from the sun. It continues only so long as the temperature to which it is subject is maintained through a relatively small range of variation. Even were we to accede that life can flourish between the freezing point and 100° Fahrenheit, this is a range of but 35° Centigrade, or a variation of little more than 10 per cent on the absolute scale of temperatures. Life is subject to gravitational and electrical forces concerning much of our environment. We know that each unit cell of this protoplasm is composed of molecules and atoms, which in turn are bundles of electrical energy. Modern medical science has made us increasingly aware of the electrical nature of this protoplasm.

What subtle effects changes in our environmental fields may have on life in any form, we do not know. Numerous experiments are making us more and more conscious of the subtleties of the electrical potentials adherent to every living cell.

The rapidly developing science of biophysics now has at its disposal many elaborate electronic devices made possible by the development of the radio industry. We have electrocardiographs which record each heart beat in terms of the electrical potential created with each throb. We have the electroencephalograph that records electrical waves generated from the activity of brain cells. Some of the most startling investigations into the electrical nature of living things have been reported from the laboratory of Dr. Harold S. Burr of the Department of Neuroanatomy of the Yale School of Medicine.

Dr. Burr's researches first came to my attention in reading an article in the press. The article stated that a Yale professor had been able to measure the electrical potential developed in a growing maple tree, and that this potential was variable and seemed to change with the moon. Being somewhat skeptical that the moon could have any influence on growing things sufficient to change the electrical potential of a tree, and discounting the newspaper write-up, I wrote to Dr. Burr directly for a copy of the scientific paper on which the news release was based. Frankly, I was more interested in what technique may have been developed for measuring such minute electrical potentials as must exist in growing things than I was in the reported correlation with the moon. The careful reading of Dr. Burr's original paper impressed me with the thoroughly scientific character of the research and resulted in a visit to his laboratory.

There I learned that more than ten years ago Professor Burr had become convinced that a properly designed electrical apparatus could be made to wrest from nature some of the secrets for the electrical basis of life. As necessity is the mother of

invention, I found that Dr. Burr had devised his apparatus to meet a definite need. The need was to gain answers to the following questions which had long been in Professor Burr's mind: Where do plants and animals get their form? How do genes bring about characteristic results? What determines the form of reproduction? These and similar questions intrigued his curiosity. He believed that if, perhaps, organic cells were determined by an electrical pattern, it should be possible to devise apparatus that could map the field surrounding living cells, and that this might yield the secret for determining their direction and rate of growth.

To measure the minute potentials developed in living cells required a new technique. Even the most sensitive of electrical meters drew so much current, relatively speaking, that any application of an ordinary meter would alter the normal behavior of the cell. In a sense, the cell would be short-circuited as soon as the meter was connected. And so Dr. Burr, with the help of his associates, devised an electrical circuit, using familiar radio parts in which it would be possible to use a meter without withdrawing any appreciable current at all from the living cells which he wished to examine. This device was a specially sensitive form of a vacuum tube microvoltmeter. To connect even this microvoltmeter to a living cell without upsetting the cell's normal function was still a problem. He had next to devise electrodes which, when in contact with the cell, would of themselves create no contact potential. He solved this difficulty by utilizing medicine droppers filled with a normal salt solution. Two such glass electrodes then made contact with the fluid of the living cell through the salt solution. Into these glass tubes, through the rubber bulb of the medicine dropper, silver wires coated with silver chloride were introduced. Since silver chloride in a salt (sodium chloride) solution will create no electrical potential, his trick was solved. The silver wires could

then be led to his microvoltmeter. He was now ready to measure true electrical potential differences in living cells. He proceeded to map the electric field around a frog's egg. The result was so interesting that he explored the electric field of thousands of such eggs. Invariably he found one point on the periphery of the cell at higher potential than all others. When the egg was hatched, he found that invariably the brain of the embryo frog would develop at this point of highest potential found in the egg before development started.

Next he rotated a salamander between the electrodes of his apparatus, and measured the alternating current resulting from the head-to-tail potential of this little protoplasmic creature, as its body passed between the specially designed electrodes. With a similar device he recorded, minute by minute and hour by hour, the changes in electrical potential developed as a kernel of corn sprouted and sent out its roots, first in one direction and then in another. With expert nicety Dr. Burr determined the potential between the two opposite ends of the corn kernel. He found invariably that the point of the kernel nearest the cob was positive with respect to the opposite end. The magnitude of the potential difference seemed definitely to correlate with the degree of vigor in the case of hybrid corn. When sprouts started, there was a marked increase in the potential gradient. Sudden fluctuations in potential would take place, with morphological changes apparent to the eye.

From frogs' eggs, salamanders, and corn kernels, Dr. Burr extended his investigations to alligator pears and to oak and maple trees. He placed electrodes two meters apart in the trunk of a young maple tree just outside his house, and connected his electrical circuit to an automatically recording meter at his bedside. Night after night, day after day, the recording pen of his meter would surge backward and forward, marking every minute change in the electrical potential which the maple tree

was generating under varying conditions of sunshine and darkness, fair weather and rain. It is from a study of the records of this maple tree that he found a periodic change in potential that, at least for a time, seemed to follow the moon.

In Figure 38 the dashed-line curve exhibits the potential changes between two electrodes in the maple tree in New Haven, Connecticut, during three days in November, 1943, and the full-

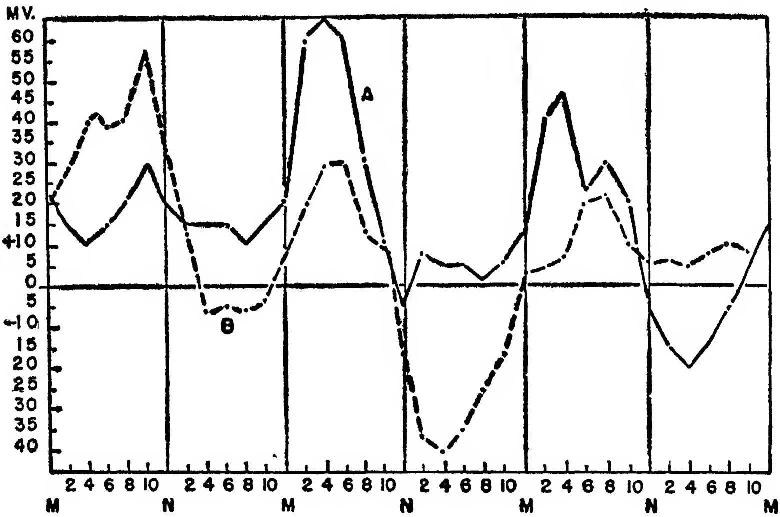


Figure 38. Hourly potential differences in a maple tree. Curve A taken during three days of August, 1943. Curve B taken at two-hour intervals during November, 1943

line curve shows the results of observations on a maple tree at Lyme, Connecticut, during three days of the preceding August. It will be seen from these curves that the range of potential in the case of the maple tree at Lyme extended from —20 to +65 millivolts, while the extreme range in the potential of the New Haven maple tree extended from +60 to —45 millivolts. In his records, Dr. Burr has traced the effects of temperature, barometric pressure, and relative humidity, but he concludes that the

peaks of electrical activity seem to be more closely associated with the phases of the moon than with any other discernible factors. It would, indeed, be startling, were subsequent records to substantiate these findings and lead to the conclusion that, after all, some electrical or ionizing stimulation should be found associated with the lunar period. The important deduction from Dr. Burr's experiments seems to be that the delicate electrical balance of a living cell is indeed affected by changes in environment. It will be many years before sufficient records have been accumulated to show whether or not tree potentials bear any relation to the sunspot cycle. If such should be the case, we would have other reasons than that of rainfall for suspecting the correlations between tree-ring formations and sunspots which Dr. Douglass' investigations have so strikingly demonstrated.

We know that every living thing survives in an electrical field which extends from the surface of the earth upward. It is this field that gives rise to the electrical potential in the atmosphere that under ordinary fair-weather conditions, as we have previously mentioned, amounts to about 100 volts per meter near the ground. If the electrical fields of living cells can be influenced by the electrical field of nature in which they must develop, there may be more truth than fancy in the hypothesis of cosmic cycles in biological behavior. Where long records of the potential gradient of the air-earth field have been carried on extensively, there is some evidence that this potential gradient varies with the sunspot cycle. The data, however, are yet scanty, and it is too early to express categorically any well-established law in this respect. As the ionization of the upper atmosphere has been found to vary definitely with sunspots, it would not be surprising if the lower air-earth current should be found also to change with the solar cycle.

The subject matter of this chapter is far from exhaustive in treating some of the new, fascinating adventures that cross the

fields of physics and biology. It is hoped, however, that the material presented has been sufficiently suggestive to stimulate further researches in a field of science of which little is yet known.

Chapter 14

SUNSPOTS AND THE ECONOMIC CYCLE

A FEW YEARS ago a banker called on me who has had at once a most distinguished career in national, political, and international affairs. He had with him a roll of charts, carefully prepared as a result of his investigations into the cyclical movement of steel prices, pig iron, and other industrial production over the years, both in this country and abroad. The similarity in the behavior pattern of the graphs, which he presented, to the sunspot curve that had been printed in my earlier book, *Sunspots and Their Effects,* was the cause of his visit. Like many others, he had been convinced that there were periodic changes in our economic cycle that suggested the possibility of some unknown factor that might be related to some fundamental cycle in nature of which we are not yet intelligently aware.

Every student of economics is familiar with the alternation of good times and hard times, booms and depressions, throughout our economic history. Whether or not such ups and downs in industry and our economic well-being are periodic because of actions taking place inherent in the course of the economic cycle itself, or whether some fundamental natural phenomena are the basis for such changes, has long been a question of discussion. Periods of abundance and scarcity, of prosperity and poverty, have been recorded in the story of civilization as far back as the days of Joseph and the time of the Pharaohs. The Biblical account recorded seven years of plenty followed by seven years of famine.

In *Dun's Review,* for October, 1937, there was reproduced a chart found in an old distillery back in the year 1885. This

chart, reproduced by permission in Figure 39, plots the paths of business activity from the year 1810 to the year 2000. Its association with a distillery is possibly due to the fact that good whisky must be properly aged, and to gauge the output years in advance required the best guessing as to future business conditions. An inspection of the graph shows in many instances remarkably good "guessing." One cannot fail to notice the years of prosperity of 1917 and 1928, and the serious depression of 1932. It might also be noted, in comparing this with the sunspot graph on page 148, that the sunspot minima of 1912, of 1923, and of 1933 are within a year of coincidence with these three "panics" depicted on the old chart. Similarly, we note the coincidence of sunspot maxima in 1907, 1918, and 1928 with boom periods on this interesting graph. Whether or not the maker of this original graph knew anything about sunspots, we shall never know.

The idea that the sunspot cycle may have something in common with economic prosperity may be traced back to the year 1878, when the economist, W. S. Jevons, presented at the British Association for the Advancement of Science a paper in which he endeavored to show evidence for a very definite cycle in economic crises, with an average interval of between ten and eleven years. He determined this interval from what he regarded as "unquestionable collapses" occurring between 1721 and 1887. This he regarded as being very near the average of the sunspot cycle, which he took to be 10.45 years. Since he could "see no reason why the human mind in its own spontaneous action should select a period of 10.45 years to vary in," he postulated that there must be some outside phenomena related to the solar cycle that was timing the industrial waves of prosperity and depression.

Believing that collapses formed the fundamental basis of the business cycle, and that these cycles were dependent upon crops, he tried to find a similar pattern in the fluctuation of agricultural

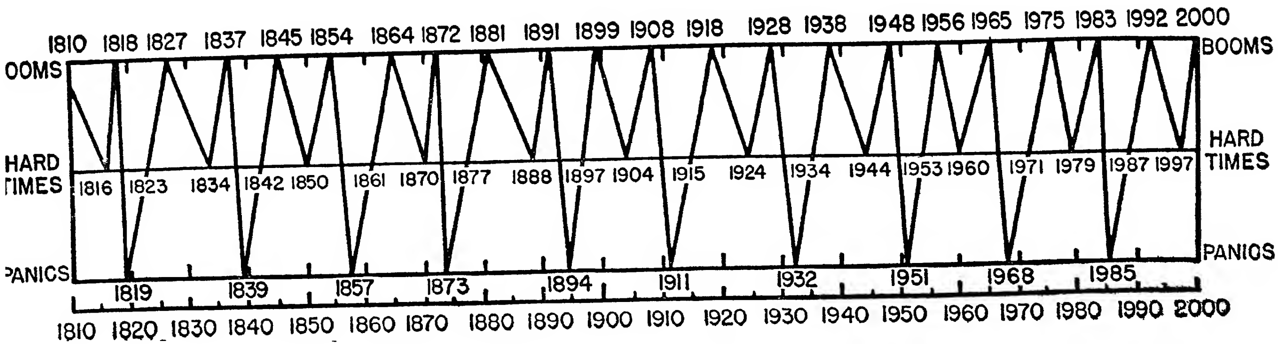


Figure 39. A chart found more than sixty years ago—1885. (Courtesy of *Dun's Review.*)

prices and in sunspots. If sunspots affected crop production and crops were dominant in economic affairs, then the chain in events connecting sunspots with business might be demonstrated.

Later, Dr. Warren Persons showed that while there was a very high correlation between agricultural yields and the physical production of crops in the United States, the corresponding correlation with total values was not a close one. Every American farmer knows how often bumper crops marketed at low prices clip the margin of earnings to such an extent that the total income from unusual agricultural yields may actually be less than when a more meager supply is marketed at more favorable prices.

In 1914, Professor H. L. Moore, writing on "Economic Cycles, Their Law and Cause," propounded another theory. He stated that there was an eight-year cycle in the annual rainfall in the United States which corresponded to a similar cycle in wholesale prices. Thus, to Professor Moore, weather was the key to agriculture, which in turn affected the ups and downs of trade in general. Dr. Warren Persons differs from Professor Moore, and insists that his own studies do not warrant the belief that the prices of agricultural commodities in themselves exhibit the periodical movements that reflect the changes in general business conditions.

Failure to find a sound basis of argument for a connection between agricultural yields and periods of prosperity and depression has led to the search for other cyclical causes. Could it be that changes taking place in the sun affect human psychology more intimately than they do agriculture, and that periodic waves of pessimism and optimism are at the foundation of business behavior?

No one doubts that business cycles depend to a very large extent upon one's mental attitude. Dr. Ellsworth Huntington, of Yale, is a persistent believer in the idea that changes in the sun affect not only the earth but even human health and be-

havior. His studies led him to believe that there is a certain dependence of mental attitude upon health. One's mental power, according to Dr. Huntington, is at its best about one year after maximum health. He assigns four years as the interval between a degree of maximum health and general business conditions. Professor Huntington bases his index of health upon the inverse death rate, a procedure which some have regarded as questionable. Nevertheless, with such a system of more or less elastic "lags," it appeared possible to make many adjustments between the business curve and the sunspot curve that would allow for many of the discrepancies and bring them much more closely into alignment.

Assuming that some psychological explanation of business fluctuations is a plausible one, then the question becomes one of finding a relationship between cycles in business psychology and cycles of cosmic origin if the hypothesis of sun and business is to be vindicated.

The idea that one's mental attitude depends upon physiological functioning is sound science. The possibility that small fluctuations in the quality of sunshine or changing electrical effects on the earth or in its atmosphere may find response in physiological and psychological reactions is to be regarded as highly speculative.

The idea that business cycles follow cycles in human behavior and the psychology of the masses is not altogether new. As far back as the early part of the nineteenth century John Stuart Mill offered a psychological explanation for business fluctuations. Ever since that time this has been one of the outstanding theories over which there has been endless debate. If the effects of the changes in the sun's behavior can be traced in the habits and actions of the masses, then, indeed, we should have some basis for business cycles following sunspots.

Some time ago Professor A. Tchijevsky, a Russian scientist, presented a startling paper at a meeting of the American Mete-

orological Society in Philadelphia. In this paper he called attention to a striking correspondence between human behavior as reflected in mass movements throughout history and the eleven-year sunspot cycle. Professor Tchijevsky is a graduate of the University of Moscow and is the author of numerous papers covering widely different subjects in astronomy, physiology, archaeology, and world history. The substance of much of his contributions has been translated by Mr. Vladimir de-Smitt, of Columbia University, to whom I am indebted for the information.

Believing that there was a certain parallelism in the cycles in the sun and significant events in the world's history, Professor Tchijevsky has endeavored to find a correlation between solar phenomena and periods of energy exhibited in the mass movements of mankind.

It is very easy, of course, with the records that have been kept of sunspots, to utilize sunspot numbers as an index of solar activity through at least two centuries. The real difficulty in Professor Tchijevsky's speculative theory came in trying to represent human psychology with any numerical coefficient that could be reliably used for comparison with the sunspot curve. That emotional excitability depends upon temperament, no one will deny. That temperament, aside from inheritance or together with inheritance, may be affected by changes in the environment of weather and of sunshine may not be too unreasonable. We note the fundamental differences in the temperament of the Nordic race and that of the Latin, whose countries differ widely in latitude, in weather, and in the amount of sunshine received throughout the year.

Edson B. Smith, Financial Editor of the *Boston Herald*, recently stated in his "investor's column," "One can scoff at the idea of seasonal influences in the field of economics, but there is plenty of evidence that climatic conditions do influence human emotions. There is an indisputable logic in the theory that

green fields and bright flowers are more conducive to cheerfulness than plowing through snowdrifts.

"In any case, whether it be the weather or some other more or less tangible influence, it is a fact that the late spring and early summer usually see a rise in the market."

If one were to attempt to find a suitable index for mass psychology, perhaps one could do no better than select the market price of securities whose fluctuations appear to be easily influenced by events which affect the human emotions. Prices rise with increasing demand, and fall as the demand lessens. When one is optimistic enough to believe that prices will be higher in the future, he buys securities either for the reason of an anticipated profit or because he desires to gain possession of those particular securities as cheaply as possible. When many investors feel the same way, bids rise, with the consequent upturn in the Dow-Jones averages.

If investors, in general, are pessimistic with regard to the future, the tendency is to sell and turn the securities into cash, lest with a fall in prices loss will be experienced. Any volume in the demand for selling invariably eases the market, and the Dow-Jones averages fall. In this way market quotations form a daily index of a cross section of the psychology of those who participate in investments. Such an index, however, must obviously represent only the cross section of those who participate in market operations, and for this reason represents strictly only a sampling of opinion of a limited class of society.

Utilizing the Dow-Jones average as an index of human psychology, it is interesting to compare the ups and downs of market fluctuations with the sunspot cycle over the last two decades. The correspondence over this interval is sufficiently striking to arrest the attention. (See Figure 40.) We find the sunspot maxima in 1937 and in 1928 corresponding within a year to the turn of the market. The depression years of 1922 and 1932 correspond within a year of the last two minima in the

sunspot curve. Our enthusiasm for this correspondence is somewhat lessened, however, should we carry the curve further back in economic history. If we did so, we should find that four

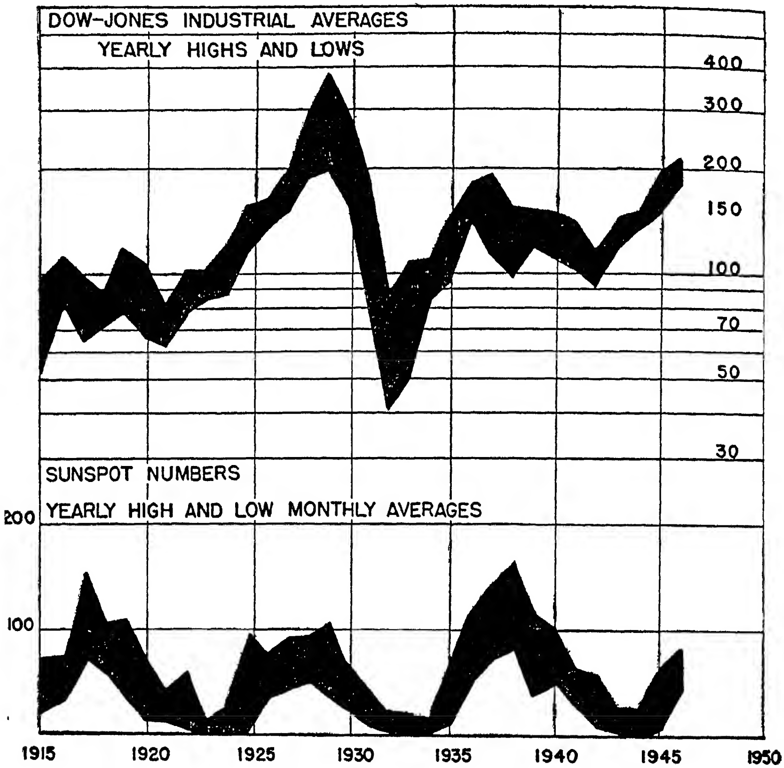


Figure 40. Dow-Jones industrial averages compared with sunspots for thirty years

out of the last five major depressions followed rather closely in the wake of sunspot maxima.

Whether or not there is any fundamental cosmic factor which is the cause of the association of the sunspot curve with the business cycle, one can think of many factors of man-made

origin that can seriously change the trend of our economic psychology. When one considers the artificially stimulated production of the war years, and the regulatory measures incident to a "planned economy," it seems the more remarkable that the ten-year trend experienced between 1923 and 1933 should have been repeated in recognizable form during the subsequent years. The relation of one business to another, dependence of production upon the general market, together with the fears and consequences of political changes, national and international, could well shift and modify the peaks and the valleys of any business curve which might in the last analysis be in some way dependent upon cycles in natural phenomena. Obviously, some businesses are much more sensitive to economic conditions than others. Consumer goods respond more promptly to buying psychology than do the heavier industries.

It is always interesting to read the columns of financial commentators in the daily news. Here one finds the current action of the market invariably interpreted in the news of the day. In the early stages of World War II, when the Central Powers were overrunning Europe, the market went down because hearts were heavy and pessimism was rife. In the later stage of the war, as the war industries got under way, the prospect of a period of high productivity was interpreted as favorable, marketwise, for stocks rose in prices. Successes of the Allied Powers at times would then be used as the explanation for sudden falls in the market, since events might be interpreted as forecasting a short duration of the war. In the later stages of hostilities, the same events might be regarded as favorable; thus our financial commentators explained the rise of the market in 1942 and 1943.

It is almost amusing to see how a certain type of event would be used by the commentators to explain a rise in the market on one occasion, and a similar event would be used to explain a fall in the market at a later date. Hindsight is always better than

foresight. Our commentators, of course, explain today's happenings on the basis of yesterday's events. One sometimes wonders if these seeming inconsistencies in reasoning are a bit artificial, and that there may be, after all, some fundamental cycle in nature which takes all events in their stride. The market curve through the years might be used as an argument that this sort of wonderment is not without some foundation.

Dewey and Dakin in their recent thought-provoking book, *Cycles* (1947) call attention to the existence of timed rhythms in our economy that persist through years of war and peace. Irrespective of the cause of such rhythms, these authors stress the importance of the recognition of rhythmic factors in an intelligent planning of future undertakings. That one of the factors in the pattern of rhythm may be the solar cycle is not to be dismissed too easily.

Unfortunately, we have no satisfactory physical picture of the mechanism which could rationally connect the ups and downs of security prices with the ups and downs of the sunspot curve. Mass psychology certainly would appear as a basis for the wider movement, but we are at a loss for any satisfying demonstration at the present time as to why changes in solar activity could change this psychology for large numbers of people simultaneously. It is possible that there may be some change in the quality of sunlight that has an indirect effect on our physiological functioning that, through the years, may be reflected in a change of attitude of mind. At the present time, however, we have insufficient scientific foundation for testing the validity of such an hypothesis.

Should evidence later appear that there are fundamental reasons for associating periods of prosperity and adversity with some fundamental cycles of nature, then we might indeed plan an economy with greater intelligence. To promote scarcity artificially at a time when nature would fundamentally favor prosperity may not be found, in the long run, to be the wisest

course. Probably the law of supply and demand is too basic throughout our natural economy to be tampered with indefinitely without undesirable results.

The history of the evolution of life on the earth through hundreds of millions of years has pretty well demonstrated that nature works with those who fundamentally cooperate with her laws. Successful living, demonstrated through the persistence of species, has indicated plainly enough that adaptation to nature is the price of survival. The industrious, either as an individual or as a species, have survived; the indolent and the shiftless creatures have become extinct. Such individuals of the animal world as gather their surplus through the growing season, maintain their activity the year around. Those that do not have no choice but to hibernate through the long winter months.

Following the pattern of nature, perhaps we should learn to store our surplus during periods of prosperity for a more equal distribution in times of adversity. Not to recognize the alternation of boom years and depression years would appear to be a poor introduction to a balanced economy. Certainly, mere day-to-day adjustment to changing conditions is not a satisfactory solution to the long-term outlook.

Perhaps in some Utopian day when we better understand the meaning of the long-term trends, some beneficent government, which can outlast the life of individuals may establish a stabilization fund that will overlap the cosmic cycles. With stable tax rates adjusted to such long-term trends, a reservoir of goods and of funds could provide such a stabilization factor. In the present political arena, however, one questions how long any government surplus could withstand spending. Until such a time as our hypothetical cosmic cycle shall have become established on a surer foundation than would be justified by present evidence, we shall probably continue for some time to make our temporary adjustments by reason of what has happened yesterday rather than by anticipation of what we may expect tomorrow.

Taking one more look at the sunspot curve, we may anticipate high solar activity until the early part of 1948. There is a sound satisfactory basis for believing that sunspot numbers will thereafter diminish until some time in 1954. For comparison, the reader may take another look at the chart recovered from an old distillery in 1885, shown in Figure 39. He is entitled to his own deductions as to the future of the economic cycle in the coming decade.

Chapter 15

SUNSPOTS, THE RADIO INDUSTRY, AND THE F.C.C.

However speculative may be the question of the relationship between sunspots and business activity in general, there is one particular business venture which for some time to come will probably be intimately tied in with sunspot activity. This is the radio industry.

We have seen in previous chapters how sunspots determine the state of the ionization of the upper air through which the electromagnetic waves of long-distance radio communications travel. We can readily appreciate, therefore, how the future of the sunspot curve is of concern to communication companies who transmit messages by radio over great distances across land and oceans. For commercial broadcasting of entertainment programs in the accepted broadcast band, sunspots are of less concern. However, in the sparsely settled rural areas of the country there are many listeners far removed from central broadcast stations who obtain much of their service in the way of radio information by means of sky-wave propagation. So, even to the commercial broadcasting company the effect of sunspots through the coming years is, after all, not of negligible interest. As long as advertisers support the bulk of our commercial programs, advertising agencies are involved, for the extreme coverage of some of the programs which they sponsor varies considerably with the sunspot cycle.

Sometimes when a program is still in the range of audibility with a receiving set tuned to maximum sensitivity, the satisfaction of a given program can be seriously impaired by the

presence of static. Static, or "noise," in radio terminology, may be thought of as electrical disturbances of man-made origin caused by the operation of noisy motors, electrical household appliances, the ignition of automobiles, and the like; or of cosmic origin, quite beyond mankind's control. Static of cosmic origin, otherwise known as "atmospherics," has been shown to vary with the sunspot cycle. It would appear that the sun is, in a sense, an electrical machine which sends out during the periods of maximum sunspot activity sufficient extraneous radiations to disturb the state of the upper atmosphere so that electrical discharges taking place above the earth's surface have the effect of invisible lightning in causing disruptive noises amidst a radio program.

It was largely due to these uncontrollable cosmic effects, as well as to static of man-made origin, that a new system of radio broadcasting and reception was invented some years ago by Major Edwin H. Armstrong, who is an outstanding figure in the development of the radio industry in America. To make possible a new form of "staticless reception," Dr. Armstrong, who incidentally holds the position of Professor of Electrical Engineering at Columbia University, originated a system of frequency modulation in broadcasting to replace the widely used system of amplitude modulation that is used in every receiver for tuning in standard broadcasts between 550 and 1500 on your radio dial.

To gain some idea of the difference between the conventional radio using amplitude modulation, and the newly developed system using frequency modulation, usually spoken of as FM, we have introduced a diagram, Figure 41, adapted from a chart used by James M. Stokley, of the General Electric Company, in *Science Remakes Our World.* In both systems of radio broadcasting, we may think of the sounds created by the artist at the microphone as a vibrational wave represented in both the upper and lower extreme left-hand frames of the

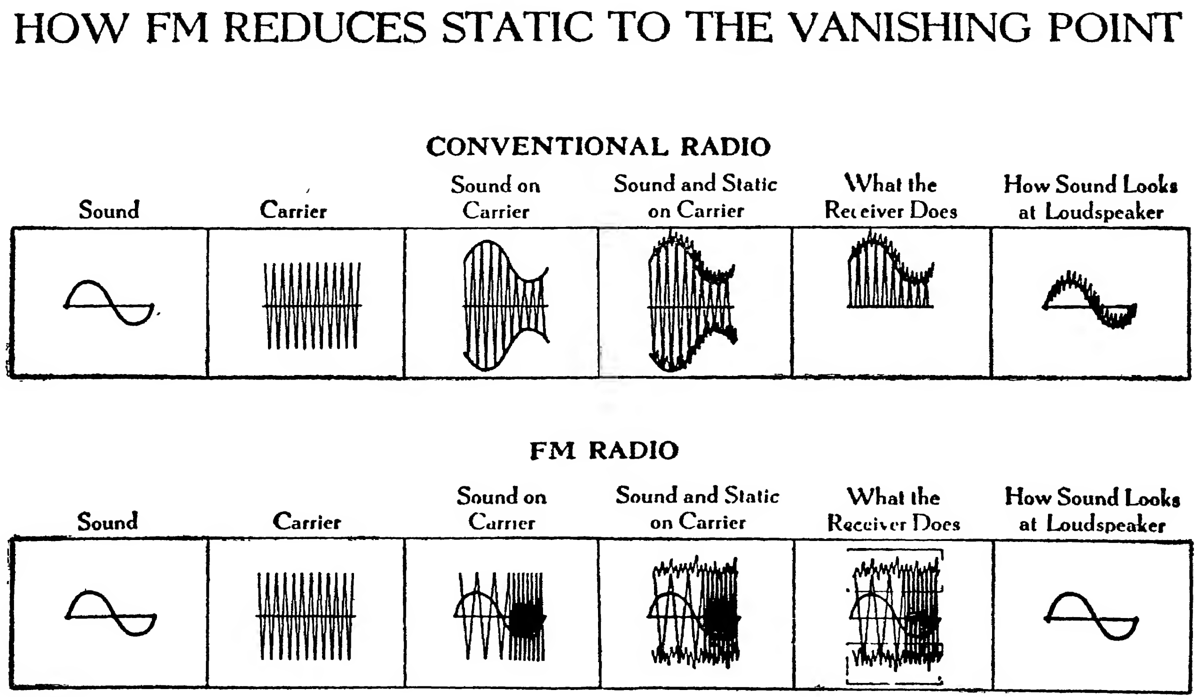


Figure 41. Comparison of FM and AM radio reception. (Courtesy of James Stokley and the General Electric Company.)

diagram. This sound wave, originating in the microphone, combines with a carrier wave of fixed frequency that is introduced into the sending apparatus at the broadcasting studio. The combination of the sound wave and the carrier wave results in a modulation represented by the varying amplitude in the third frame of the upper diagram illustrating conventional radio performance. It will be noted here that the frequency (spacing between waves) of the carrier is not changed by the superposition of the sound wave, but that the height of each little wavelet in the carrier, which we may call the amplitude, varies with the variation of the sound wave superimposed upon it. In the case of FM radio, the apparatus is so designed that the combination of the sound wave with the carrier wave changes the frequency (the space between the carrier waves), while the amplitude (height) of the carrier waves remains constant. The third frames in the upper and lower diagrams of Figure 41 show where the difference is introduced between the conventional amplitude modulation, or AM, reception, and frequency modulation, or FM, reception.

Let us now see what static or atmospheric interferences do to these two types of wave as shown in the fourth frame of the two diagrams. In the conventional, or AM radio, the static is represented as a saw-tooth line superimposed upon the modulated carrier wave, changing still more the variations in amplitude or height of the waves. In FM reception, static similarly superimposes itself as a saw-tooth curve on the top and bottom of the fixed amplitude carrier wave, but in nowise does it change the varying frequency represented by the variable spacing in the carrier. It is this variation in frequency, or spacing, of the waves that is responsible for reception at the receiver.

In the fifth frame we see what the conventional receiver does to the conventional AM radio wave. It allows the saw-tooth variations to come through so that they are reproduced in

the amplitude of the sound wave in frame six that comes out of the loud-speaker. In the case of FM, a certain radio tube is introduced that cuts off the tops and the bottoms of the carrier waves just above and below the extreme sweeps of the sound wave, and does not allow the static, which is responsible for the saw-tooth tops and bottoms of the carrier wave, to come through at all. This special service tube, which limits the amplitude of the carrier wave to the two parallel lines just above and below the sound wave, is called the "limiter" in our FM receivers. Thus, as the picture shows, static is eliminated and the sound wave comes out of the loud speaker in its pure form, a faithful reproduction of the sound wave at the microphone.

One who has become accustomed to listening to radio programs, especially in the summer season, by means of both AM and FM reception, knows the great superiority of the frequency modulation system. Vacuum cleaners, refrigerators, oil burners and electric razors, which, unless carefully shielded, send out their electrical disturbances to interfere with the ordinary radio, have no effect on the FM receiver. Thunderstorms that cause such heavy crackling, and which render almost inaudible even the reception from our metropolitan broadcasting stations, become nonexistent when the listener tunes in on FM reception. All this is an excellent illustration of how, after gaining information of the natural causes for disturbances of radio, man has used his ingenuity in devising a system of radio broadcasting and reception that can by-pass the deleterious effects of nature's antics. FM broadcasting is a boon to farmers and rural communities. To listeners often situated many miles from conventional broadcast stations, atmospheric static, especially during the thunderstorm season, makes the old-style radio tuned to a distant station almost useless.

With the frequency modulation system invented, it was no easy matter to solve the problem of its commercialization. In

spite of all the many frequencies at which radio waves can be transmitted, the allocation of these frequencies is a matter of national and international concern, lest conflicting broadcasting stations should interfere with one another in filling the air with programs or communications on similar wave lengths or near-by frequencies. The conventional broadcasting stations of the United States, stretching from Eastport (Maine) to Los Angeles, and from Miami to Seattle, had already filled the available part of the radio spectrum allocated to commercial broadcasting. This is the region of 550 kilocycles to 1,500 kilocycles. If a new kind of frequency modulation radio broadcasting were to be made nationally available, it would have to utilize waves of frequencies not already taken by previous allocations.

Shortly after the early days of radio broadcasting, with the demand for more and more stations to be heard, the United States Government set up in Washington the Federal Communications Commission, otherwise known as the F.C.C., to take charge of the allocation of suitable frequencies for the various purposes of the radio industry. This commission, like a board of judges, was to have recourse to full information, and the advice of the best technical experts which the radio profession could provide. Only by so doing could it hope to pass fair and impartial judgment on the relative merits of the many demands for new radio stations that came to be almost legion in their appeals for broadcasting frequencies. The commercial future of the new frequency modulation radio system had, therefore, to be laid at the doorstep of the Federal Communications Commission.

Some of us who frequently use railroads in nationwide travel, or who depend upon train schedules for the arrival of goods by freight or express, often marvel at the intricate problems of traffic control in the dispatcher's office of the large railroad centers. By an elaborate mechanism, the dispatcher

knows not only the time of arrival and departure of every train scheduled, both freight and passenger, but the location of every train on every track, and the allocation of every car to every train. A system, which is a bewilderment to the layman, has become so carefully organized as to make possible the integration of hundreds of railroad lines into an entire continental system. Equally bewildering to the uninitiated are the traffic problems of our rapidly augmenting air lines, where the location of every plane on the ground and in transit must likewise be known to the traffic manager. In overcast weather, when scores of planes are seeking landings at the same field, radio communications must constantly be maintained with every pilot, and directions given for safe maneuvers at various altitudes, to avoid interference so that each pilot in turn may be guided to the runway through instruments which make blind-flying possible.

The problem of the train dispatcher, and of the traffic manager for our air lines, is not unrelated to the problem of the Federal Communications Commission in Washington. This commission must keep channels open for radio communication in all parts of the radio spectrum from frequencies of 10 kilocycles to frequencies of 200,000 kilocycles and more. Provision must be made for the ever-growing needs of new devices employing radio waves, while air waves continue to furnish service to commercial communications, weather reports, ship-to-shore telephones, maritime aids, transmission of facsimiles or pictures by radio, radio teletypes, transatlantic radio telephone, police communication, the standard radio broadcasts, and overseas short-wave broadcasts. All this is in addition to Government requirements of Army, Navy, Coast Guard, and the airways. Now, frequency modulation broadcasts and the broadcasting of television add to a bewildering array that calls for immediate attention and demands the most careful study for fair evaluation in the solution of every new requirement.

When one takes further into consideration that, unlike railroad systems with fixed tracks, switches, and sidings, the tracks of the electromagnetic waves of radio are constantly changing with the time of day, with the season of the year, and with the sunspot cycle, we can appreciate something of the technical intricacies of the problem of allocatiòn quite aside from the commercial aspects.

The first specific body of the Government charged with the allocation of frequencies for radio programs was the Federal Radio Commission, established by an act of Congress in 1927. This original commission was reorganized into the Federal Communications Commission in 1934. In its enlarged form, it was to assume responsibility for all communication problems involving not only radio waves, but communication via telephone and telegraph as well.

The merits of FM broadcasting were first brought to the attention of the commission by the inventor, Major Edwin H. Armstrong, in 1936, but it was not until May 20, 1940, that the commission removed FM from the realm of experimental radio into the field of commercial operation and made available thirty-five channels, each two hundred kilocycles wide for commercial use in the continuous band of the radio spectrum stretching from 43 to 50 megacycles. At the same time, five additional channels were allocated for non-commercial educational FM broadcasting between 42 and 43 megacycles. By October, 1944, forty-six commercial FM broadcasting stations had been licensed, and the applications for FM stations that have come in since can be numbered in the hundreds.

In January, 1945, with the increased demand for more channels for FM and the coming television broadcasts, the commission undertook a resurvey of the entire radio spectrum. It appointed a Radio Technical Planning Board consisting of several panels, each of which would represent the several

interests of the radio industry that would be concerned with any reallocation program.

Early in its proceedings, the Federal Communications Commission suggested that FM broadcasting be moved from its established region of 42-50 megacycles to at least double these frequencies. The matter was referred to the Radio Technical Planning Board, which gave careful consideration to the whole problem in view of the ever-increasing pressure for accommodating more frequencies in the radio spectrum. In 1944, the Radio Technical Planning Board reported, by a vote of twenty-seven to one, in favor of allowing the FM frequencies to stay at their established location. Extended hearings were held in Washington, and in January, 1945, the F.C.C. presented their tentative allocations assigning FM to the high-frequency channels extending from 84 to 102 megacycles. The channel from 44 to 50 megacycles was allotted, with other regions, to the future development of television.

With the appearance of these proposed allocations, strenuous objections were raised by the FM interests on two grounds. First, the service that could be rendered the public on the higher frequencies would be seriously restricted on account of transmission limitations. It was generally agreed that the area of coverage by a station of given power would be decreased as the frequency was increased. Second, the new allocations meant that over 400,000 existing FM receivers in the hands of the public, representing an investment of $72,000,000, would be rendered obsolete overnight if such a change in frequency were to be made.

The Commission's argument in favor of the change in frequencies was based on such observational material as was then available that indicated that certain interferences noted in the 40-50 megacycle region would be less likely to occur in the 84-102 megacycle band. Reports had been coming in to the

Commission showing that police calls broadcast on a frequency of 40 megacycles had been heard, on occasions, in distant cities hundreds of miles away. Furthermore, tests made at Atlanta, Georgia, and at other stations, indicated that the FM station WGTR, broadcasting on 44.3 megacycles, located at Paxton, Massachusetts, could be heard a thousand miles distant, due, presumably, to sky-wave reception.

We must remember that the high-frequency waves used in FM reception were originally supposed to travel close to the earth and not be received much beyond what would be the line-of-sight or optical horizon. In our discussion of tropospheric reception in an earlier chapter (Chapter 5), we called attention to the importance of refraction, or bending, of the radio waves traveling in the troposphere. By means of refraction, these tropospheric waves actually can be received two to three times as far as the supposed line-of-sight distance. This might range from seventy to one hundred miles or more. In the early days of very high frequency broadcasting, no engineer would have supposed that any reception over so great a distance as a thousand miles could possibly be received. This is because long-distance reception presupposes the reflection of a sky wave from the ionosphere. The high-frequency waves used in FM and in television were supposed to be of such short wave length that even such sky waves as went upward would penetrate the ionospheric layers and not be returned to earth at all. Observational evidence, however, could not be brushed aside. This called for some explanation. It was, therefore, conceded, that under certain conditions, even 40-50 megacycle waves might be turned back by the upper ionized layer commonly called the F_2 layer, provided the ionization there was of sufficient density. Another factor also entered into the argument. This was the idea that the existence of patches of ionization in the lower, or E layer, which we have previously referred to as "sporadic E," could form a reflecting surface from which skywave trans-

mission of even these very high frequency waves might be turned back, thus accounting for the long-distance interference in FM reception.

In view of the many objections raised to changing FM's frequencies, the F.C.C. again referred the matter for reconsideration by the Radio Technical Planning Board. This board of experts again gave its careful attention to the arguments that had been advanced by the technicians of the F.C.C. They re-examined all the data that had been presented at the hearings, and in 1945 reported back to the F.C.C. The Radio Technical Planning Board, by a vote of twenty-one to one, again recommended that FM broadcasting be allowed to remain in substantially the 42-50 megacycles band originally established.

The Federal Communications Commission then reopened hearings in Washington. Both sides of the controversy were again represented by experts in the theory of radio wave propagation, and by representatives of the radio industry. The controversy centered about the interpretation of the observational material available. There were differences of opinion as to the number of hours of interference that might be anticipated in FM reception in its original allocation. Many of the interferences reported were but momentary, in the nature of what is technically known as "bursts." These might last from a fraction of a second to a few seconds. Occasionally, intermittent interference from a distant program might be heard for as much time as eight minutes in a half hour's observation.

It was then that sunspots were brought into the discussion. Experts for the Commission argued that if the amount of interference already reported had occurred at sunspot minimum (1942-1944), then at sunspot maximum, with a higher degree of ionization in the F_2 layer, and with more frequent occurrences of sporadic E, the amount of interference that would be experienced would be far more serious. Dire results were pre-

dicted from ionospheric reflections of FM broadcasts during the next sunspot maximum if FM was to remain in the 40-50 megacycle band. The F.C.C.'s technical expert envisioned solar activity at the next sunspot maximum to be far higher than at the last maximum, basing his remarks on Gleissberg's prediction, to which reference was made in Chapter 11. In our discussion of Gleissberg's prediction in that chapter, we called attention to the fact that on the basis of his hypothesis the theoretical calculations for the maximum solar activity of the last two sunspot cycles yielded values for 1937 and 1928 far above the sunspot numbers which actually were observed in those years of sunspot maxima. Other experts challenged the position taken, indicating evidence that solar activity of the next sunspot cycle might be less than that anticipated, and that the conclusions based on the extrapolated sunspot curve were not necessarily valid.

Another question for which there seemed to be no immediate answer was what the effect of increased ionization in the E and F_2 layers might be on the actual field intensities of transmitted waves. Investigations thus far have failed to show any simple correlation between ionospheric densities in the F_2 layer and the actual field intensities that may be anticipated at these higher frequencies at a given distance for a given amount of radiated power. Furthermore, search has been made for relationships between the amount of sporadic E occurrences and sunspots, and the relation does not appear from present data to be a simple one. What sunspots may do to FM reception at the peak of solar activity appears to be problematical until sufficient data at these high frequencies have been recorded for a considerable part of the sunspot cycle. Such data should include at least a year's observations around sunspot maximum to make any judgment sound. A serious question was raised, therefore, in moving FM from its established frequency, where performance had been good, to a relatively untried region, about

which we knew so little. Major Armstrong emphasized that in the early experimental days of his frequency modulation he had had unsatisfactory results when obliged to operate on 109 megacycles, but that FM service had been most successful after the F.C.C. had allocated the lower frequency band of 42-50 megacycles.

Furthermore, it was a question of whether the allocation to the higher frequencies would entirely remove all interference that might be due to cosmic factors beyond our control. Near the sunspot maximum in 1937, reception from the television station at Alexandria Palace, in England, broadcasting on 41.5 megacycles, was reported as received at Riverhead, Long Island. Think how disconcerting to have the telecast of a World Series game interrupted by a hansom cab from London running first base in the ninth inning! This station was frequently picked up during the years 1937, 1938, and 1939 by RCA monitors, although the power output of the antenna was but 30 kilowatts. G. W. Pickard also, on occasion, found the same station coming in at his laboratory at Seabrook Beach, New Hampshire, during the years 1938 and 1939.

During the proceedings of the Commission, comments were requested from Dr. John H. Dellinger, Chief of the Interservice Radio Propagation Laboratory at the National Bureau of Standards, and Chairman of the American Section of the International Scientific Radio Union. Concerning the relative interference that might be anticipated on the 40-50 megacycle band, as compared with anticipated interference in the 80-100 megacycle region, Dr. Dellinger remarked: "The point in question is that the frequencies concerned are sometimes affected by long-distance interference, contrary to an expectation that was widely held at one time, and there is a fear that this interference may be so great as to seriously impair the usefulness of those frequencies for broadcasting. Essentially, the Panel appears to request that I inform it whether that fear is well-

founded. I believe I may with propriety respond to this request, and the answer is that the fear is not well-founded.

"During certain years of the sunspot cycles, F_2-layer transmission at those frequencies occurs over long distances for short parts of the day, and sporadic E transmission occurs at irregular times in all years. The phenomenon of very short bursts of long-distance interference appears to be closely associated with, and possibly a manifestation of, sporadic E transmission. The extent of these effects, however, is not such as to seriously impair the value of these frequencies. It may also be stated that no radio frequencies are free from transmission vagaries."

At the close of the hearings, the Federal Communications Commission again went into a huddle. The decision was not an easy one. Moving FM upstairs in the radio spectrum meant curtailed service for each area, but also, for this very reason, the change would make possible the assignment of frequencies to many more prospective FM broadcasting stations than could be otherwise accommodated.

In July, 1945, the Commission published their decision for the allocation of frequencies from 25,000 kilocycles to 30,000,000 kilocycles. (See Figure 42.) In this allocation, FM was assigned a band of frequencies from 88 to 106 megacycles. This decision, of course, renders obsolete many hundreds of thousands of FM receivers, and requires large expenditures for changing over all transmitting equipment in all previously existing FM broadcasting stations. Records of performance in the coming years will indicate the wisdom of the arguments upon which such a decision was made.

During the transition period, before new FM receivers are manufactured in sufficient numbers to meet the public demand, we have the satisfaction of knowing that music goes forth from the new high-frequency radio towers, like fragrance on the desert air, with practically no listeners to enjoy the program.

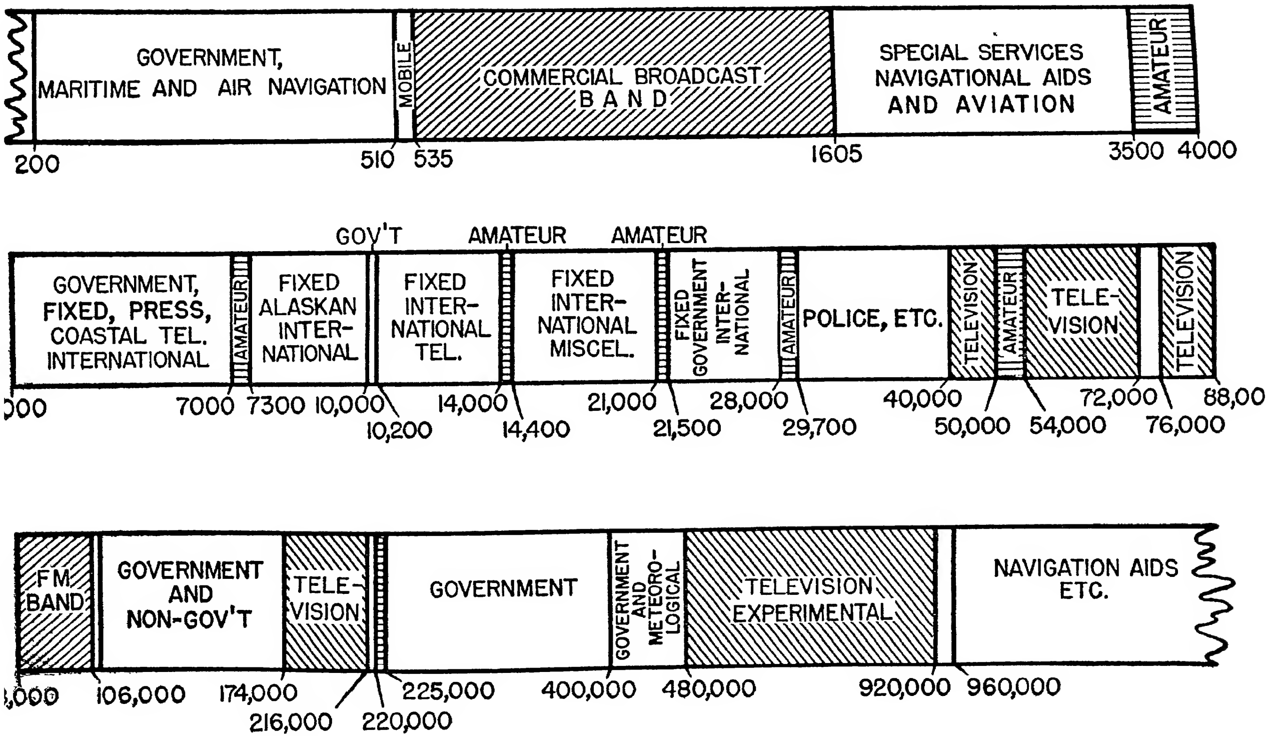


Figure 42. F.C.C. frequency allocations as of July, 1945

Before the present high state of sunspot activity is past, perhaps a sufficient number of new FM receivers will have been distributed, and sufficient data gathered, to know whether or not interference from stations in Rochester, New Orleans, or Atlanta may interrupt, with uncanny bursts, symphonic programs broadcast from some New York network. The probability is that such interruptions will be so infrequent, as compared to the static that FM intrinsically eliminates, that our enjoyment of programs on this new wonder of radio will ignore such infrequent bursts from sporadic E or the F_2 layer as may be detectable only to the experts hunting for such elusive cosmic game.

Chapter 16

COSMIC TERRESTRIAL RESEARCH

IN THE PRECEDING CHAPTERS of this book we have surveyed many aspects of the relation of the earth to the sun and sunspots. We have become increasingly conscious that the well-being of mankind, and many activities on the surface of our planet, are inextricably related to the sun. We have looked into the source of the sun's energy and have found that the ultimate storehouse for such energy is within the atom itself.

We have seen that the whole science of radio communication has been made possible through the action of sunshine upon the high upper atmosphere that surrounds the earth; and that the many vagaries in radio communication conditions can be traced directly to changes in the sun that accompany the appearance of sunspots. We have discovered recurrent cycles in solar activity, so that it is possible to predict, with a reasonable degree of certainty, years of maximum sunspottedness and years of minimum sunspots.

It is within the present generation that the whole science of radio communication has come to be established. It is only in the last dozen years that systematic observations of critical frequencies have been made for the observation of the ionic density of the upper layers of the atmosphere. Perhaps these measurements, more than anything else, have emphasized the close connection between sunspots and business activities on the earth. Radio communication has become such an essential part of all industry that interruption to our communication channels by happenings on the sun has many ramifications.

When large solar disturbances are under way, news agencies are crippled in their overseas releases, air traffic delayed, and even markets affected. On a recent occasion, brokers reported that grains were bid up in Winnipeg while the grain market was falling in Chicago. This was because telegraphic connections between the two pits were severed by the electrical disturbance accompanying the sunspot of February 7, 1946, the largest in sunspot history. Such evidence makes us conscious, as never before, of our cosmic environment and the growing importance of interrelating knowledge in many diversified fields of science.

It was with the hope of contributing in some measure to investigations in the field of Cosmic Terrestrial Relationships that there was set up at the Massachusetts Institute of Technology, ten years ago, a fund for Cosmic Terrestrial Research, to make possible certain investigations that might add to our knowledge in this important field. The fund was made possible through contributions of certain friends of the Institute. In 1939 and 1940 a special laboratory was built in the suburbs of Boston, where observational work could be carried on in a location removed from the interferences incident to an industrial area. The primary purpose of the laboratory was to be the gathering and study of data concerning such relationships as may exist between cosmic phenomena exterior to the earth and terrestrial phenomena that may result from or vary with changes in the earth's exterior environment.

Provisions were made for the recording of radio field intensity data over different paths at different frequencies as a basis for the study of actual performance of radio communication as it may be affected by sunspots and other forms of solar activity. Apparatus has also been installed for a study of the electrical conditions of the lower atmosphere, and for recording the intensity of cosmic rays in three parts of the cosmic ray spectrum. Measurements have also been made of

the varying electrical potential gradient near the earth's surface, and of the silent electrical discharges taking place between the earth and its atmosphere.

In addition, systematic observations are made in the apparent shift in direction of the beam of a commercial air beacon located ten miles from the laboratory. These investigations have already yielded interesting results. As is generally known, the antenna of a radio air beacon is so arranged that the Morse code signals for the letters A and N are sent out from adjacent quadrants, such as northwest and southwest. A pilot homing exactly on the beam hears neither of these signals, but a constant hum resulting from the overlapping of both signals received simultaneously and with equal intensity. If the pilot is north of the axis of the beam, the dot-dash of the letter A predominates; if he is south of the beam, the dash-dot of the letter N predominates. The relative strength of these two signals heard from a point off the axis is, in a measure, an indication of how far the plane may be from the axis of the beam. The Needham laboratory lies slightly north of the axis of the beacon under observation. The field strength of the A signal, compared with that of the N signal, is measured hourly. Every effort is made at the sending antenna to maintain the output of the two signals constant, yet the ratio of these two signals, as observed at the laboratory, shows definitely a diurnal and seasonal variation. The ratio of A/N rises steadily after sunrise to a maximum value shortly after noon, and thereafter diminishes toward sunset. Under abrupt meteorological changes, the value of the ratio has been found to change systematically with the passing of a storm center. If one were to interpret the change in the ratio of A/N as equivalent to a change in the bearing of the direction of the beam, it can be said that during severe storms the apparent direction of the beam has been observed to shift by as much as ten degrees from its normal location with respect to the laboratory.

Careful consideration has been given to the possibility of fortuitous changes at the beacon itself, including the possible effect of unequal electrical insulation in the antenna system during rain or snow. The results, however, more definitely point to dielectric changes in the lower atmosphere, or to changes in ionization conditions in the tropospheric layers. Irrespective of any practical considerations that might be applicable to problems of aviation, it is believed that further investigations of this nature may yield important information as to atmospheric-electric conditions that may correlate with meteorological or other phenomena under observation at the laboratory.

Because of the fact that television waves have been found to be absorbed by tree growth and vegetation, records are made of the varying electrical conductivity of a specimen tree on the grounds of the laboratory. The conductivity varies with the time of day, with the season of the year, and with the meteorological elements. Provision has been made for the observation of variations in geomagnetism that are known to show close correspondence with changes in the ionosphere and in sunspot activity, and even in the counts of cosmic rays that reach the earth from interstellar space. With the accumulation of the records, we are made constantly aware of the interrelation of many geophysical phenomena. Analysis of the records of one group of data frequently suggests the method of study of other phenomena which may be related, but the relationship of which may or may not be easily discerned.

Twelve years ago in *Earth, Radio and the Stars,* I ventured to suggest that we had need of a new term for bringing the various sciences together into a more complete knowledge of the earth and its relation to its cosmic environment. I ventured the term *cosmecology*. Ecology is a familiar term to the student of biology who seeks to study the effects of environment on the characteristics of plant and animal life. When, therefore,

we consider the relation of the earth to its cosmic environment, we might logically join the words *cosmic* and *ecology* into a single term. Whatever label we use, we are, in a sense, approaching the world in which we live with a new viewpoint—the interrelationships of a vast body of knowledge of cosmic phenomena; phenomena that in the end concern the earth and all activities upon it. In the largest sense, we are dealing with problems of terrestrial physics, tracing that field into every contact which the earth makes with established science. We are concerned with problems that overlap those of the geologist, the physicist, the meteorologist, the radio engineer, and the astronomer. Perhaps, hardly less directly, we shall find that the biologist and the economist will soon participate in the quest for answers which are so often sought in so broad a field of knowledge.

During the past generation, science has passed through a highly analytical age. We have learned to break down matter into its ultimate constituents. Physics has done that which chemistry alone could not have performed. With the mass spectrograph it has discovered isotopes; with its cyclotrons and betatrons it has split the atom, even penetrating the nucleus and releasing atomic energy. It seems already that we are beginning to sense a synthetic age in which the results of highly specialized fields of science will be brought together into larger aggregations of knowledge for the solution of problems too far-reaching to be solved by any single group of specialists. We shall devise new methods of analysis, and new instruments and apparatus for prying into the secrets of the invisible. Technique, such as that which gave us the electron microscope that measures microorganisms in terms of microns, and radarscopes that make possible the visualization of microseconds, will undoubtedly place new tools at our disposal for developing further specialized knowledge. However, with the overwhelming wealth of material data, we shall do well to develop and encourage the cosmic outlook, lest in writing elaborate treatises

on the trees themselves we escape the significance of the forest in which they stand.

Perhaps, in this era of high specialization, we have lost something of the viewpoint of the masters of science of yesterday who called themselves naturalists and philosophers. A hundred years ago, such detailed knowledge as we have today could scarcely have been pictured. The problem of interrelating the fields of natural phenomena in the days of da Vinci, Newton, Darwin, Agassiz, Huxley, Helmholtz, and Faraday, was far simpler than today. We have been masters in training technicians in all fields of science, but we need to constantly bear in mind the spirit of these masters. We need to train scientists as well as technicians—scientists who, while specialists in their own field, continually cultivate that attitude of thinking and that habit of open-mindedness which so recognizes the interrelations of diversified fields as to lead the way to the solution of problems that no single territory of knowledge alone can ever solve.

Science, perhaps, has been altogether too slow in apprehending the significance of the earth's cosmic environment as an important factor in the geophysics of our planet. Moreover, we are becoming increasingly aware that man himself is a highly articulated organism, whose activities, and even whose metabolic processes, are quite dependent upon the quantity and quality of the sun's radiation and other factors in his terrestrial environment. The mysterious electron, that fundamental building block of matter which dances in our radio tubes to the tunes of our favorite orchestra, dances likewise in the atoms of the distant stars, in the vast interstellar spaces, and even in man himself. We are entering upon a strange new world of thought in science, perhaps as strange as was the Copernican doctrine of a heliocentric universe to the medieval mind of three hundred years ago.

What implications the future may hold we cannot now fore-

see. Perhaps a note of caution should be sounded lest the over-enthusiastic indulge in unwarranted speculation. To the less imaginative Horatios, Hamlet yet speaks:

> "*. . . . stranger give it welcome.*
> *There are more things in heaven and earth, Horatio,*
> *Than are dreamt of in your philosophy.*"

APPENDIX

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RELATIVE SUNSPOT NUMBERS

As supplied by Swiss Federal Observatory, Zurich, Switzerland, and Published in *Monthly Weather Review,* Vol. 30 *et seq.*

Date	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1749	58.0	62.6	70.0	55.7	85.0	83.5	94.8	66.3	75.9	75.5	158.6	85.2	80.9
1750	73.3	75.9	89.2	88.3	90.0	100.0	85.4	103.0	91.2	65.7	63.3	75.4	83.4
1751	70.0	43.5	45.3	56.4	60.7	50.7	66.3	59.8	23.5	23.2	28.5	44.0	47.7
1752	35 0	50.0	71.0	59.3	59.7	39.6	78.4	29.3	27.1	46.6	37.6	40.0	47.8
1753	44 0	32.0	45.7	38.0	36.0	31.7	22.0	39.0	28.0	25.0	20.0	6.7	30.7
1754	0.0	3.0	1.7	13.7	20.7	26.7	18.8	12.3	8.2	24.1	13.2	4.2	12.2
1755	10.2	11.2	6.8	6.5	0.0	0.0	8.6	3.2	17.8	23.7	6.8	20.0	9.6
1756	12 5	7.1	5.4	9.4	12.5	12.9	3.6	6.4	11.8	14.3	17.0	9.4	10.2
1757	14.1	21.2	26.2	30.0	38.1	12.8	25.0	51.3	39.7	32.5	64.7	33.5	32.4
1758	37.6	52 0	49.0	72.3	46.4	45.0	44.0	38.7	62.5	37.7	43.0	43.0	47.6
1759	48.3	44.0	46.8	47.0	49.0	50.0	51.0	71.3	77.2	59.7	46.3	57.0	54.0
1760	67.3	59.5	74.7	58.3	72.0	48.3	66.0	75.6	61.3	50.6	59.7	61.0	62.9
1761	70.0	91.0	80.7	71.7	107.2	99.3	94.1	91.1	100.7	88.7	89.7	46.0	85.9
1762	43.8	72.8	45.7	60.2	39.9	77.1	33.8	67.7	68.5	69.3	77.8	77.2	61.2
1763	56 5	31.9	34.2	32.9	32.7	35.8	54.2	26.5	68.1	46.3	60.9	61.4	45.1
1764	59 7	59.7	40.2	34.4	44.3	30.0	30.0	30.0	28.2	28.0	26.0	25.7	36.4
1765	24.0	26.0	25.0	22.0	20.2	20.0	27.0	29.7	16.0	14.0	14.0	13.0	20.9
1766	12.0	11.0	36.6	6.0	26.8	3.0	3.3	4.0	4.3	5.0	5.7	19.2	11.4
1767	27 4	30.0	43.0	32.9	29.8	33.3	21.9	40.8	42.7	44.1	54.7	53.3	37.8
1768	53.5	66.1	46.3	42.7	77.7	77.4	52.6	66.8	74.8	77.8	90.6	111.8	69 8
1769	73.9	64.2	64.3	96.7	73.6	94.4	118.6	120.3	148 8	158.2	148.1	112.0	106.1
1770	104.0	142.5	80.1	51.0	70.1	83.3	109.8	126.3	104.4	103.6	132.2	102.3	100.8
1771	36 0	46.2	46.7	64.9	152.7	119.5	67.7	58.5	101 4	90.0	99.7	95.7	81.6
1772	100.9	90.8	31.1	92.2	38.0	57.0	77.3	56.2	50.5	78.6	61.3	64.0	66 5
1773	54.6	29.0	51.2	32.9	41.1	28.4	27.7	12.7	29.3	26.3	40.9	43.2	34.8
1774	46.8	65.4	55.7	43.8	51.3	28.5	17.5	6.6	7.9	14.0	17.7	12.2	30.6
1775	4.4	0.0	11.6	11.2	3.9	12.3	1.0	7.9	3.2	5.6	15.1	7.9	7.0
1776	21.7	11.6	6.3	21.8	11.2	19.0	1.0	24.2	16.0	30 0	35.0	40.0	19.8
1777	45.0	36.5	39.0	95.5	80.3	80.7	95.0	112.0	116.2	106.5	146.0	157.3	92.5
1778	177.3	109.3	134.0	145.0	238.9	171.6	153 0	140.0	171.7	156.3	150.3	105.0	154.4
1779	114.7	165.7	118.0	145.0	140.0	113.7	143.0	112.0	111.0	124.0	114 0	110.0	125.9
1780	70.0	98.0	98.0	95.0	107.2	88.0	86.0	86.0	93.7	77.0	60.0	58.7	84.8

RELATIVE SUNSPOT NUMBERS—(*Continued*)

Date	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1781	98.7	74.7	53.0	68.3	104.7	97.7	73.5	66.0	51.0	27.3	67.0	35.2	68.1
1782	54.0	37.5	37.0	41.0	54.3	38.0	37.0	44.0	34.0	23.2	31.5	30.0	38.5
1783	28.0	38.7	26.7	28.3	23.0	25.2	32.2	20.0	18.0	8.0	15.0	10.5	22.8
1784	13.0	8.0	11.0	10.0	6.0	9.0	6.0	10.0	10.0	8.0	17.0	14.0	10.2
1785	6.5	8 0	9.0	15.7	20.7	26.3	36.3	20.0	32.0	47.2	40.2	27.3	24.1
1786	37.2	47.6	47.7	85 4	92.3	59.0	83.0	89.7	111.5	112 3	116.0	112.7	82 9
1787	134.7	106.0	87.4	127.2	134.8	99 2	128.0	137 2	157.3	157.0	141.5	174.0	132.0
1788	138.0	129.2	143.3	108.5	113 0	154 2	141.5	136 0	141.0	142.0	94.7	129.5	130.9
1789	114.0	125.3	120.0	123.3	123.5	120 0	117.0	103.0	112.0	89.7	134.0	135.5	118.1
1790	103.0	127.5	96.3	94.0	93.0	91.0	69.3	87.0	77.3	84.3	82.0	74.0	89.9
1791	72.7	62.0	74.0	77.2	73.7	64.2	71.0	43.0	66.5	61.7	67.0	66 0	66.6
1792	58.0	64.0	63.0	75.7	62.0	61.0	45.8	60 0	59.0	59.0	57.0	56 0	60.0
1793	56.0	55.0	55.5	53.0	52 3	51.0	50.0	29 3	24.0	47.0	44.0	45.7	46.9
1794	45.0	44.0	38.0	28.4	55.7	41.5	41.0	40 0	11.1	28.5	67.4	51.4	41.0
1795	21.4	39.9	12.6	18.6	31.0	17.1	12.9	25.7	13.5	19.5	25.0	18 0	21.3
1796	22.0	23.8	15.7	31.7	21.0	6.7	26.9	1.5	18.4	11.0	8.4	5.1	16.0
1797	14.4	4 2	4.0	4.0	7.3	11.1	4.3	6.0	5.7	6.9	5.8	3.0	6.4
1798	2.0	4 0	12.4	1.1	0.0	0.0	0.0	3.0	2.4	1.5	12.5	9.9	4.1
1799	1.6	12.6	21.7	8.4	8.2	10.6	2.1	0.0	0.0	4 6	2.7	8.6	6.8
1800	6.9	9.3	13.9	0.0	5.0	23.7	21.0	19.5	11.5	12.3	10.5	40.1	14.5
1801	27.0	29.0	30.0	31.0	32.0	31.2	35.0	38 7	33.5	32.6	39.8	48.2	34.0
1802	47.8	47.0	40.8	42.0	44.0	46.0	48.0	50.0	51.8	38.5	34.5	50.0	45 0
1803	50.0	50.8	29 5	25.0	44.3	36.0	48.3	34.1	45.3	54.3	51 0	48.0	43.1
1804	45.3	48.3	48.0	50.6	33.4	34.8	29.8	43.1	53.0	62 3	61.0	60.0	47.5
1805	61.0	44.1	51.4	37.5	39.0	40.5	37.6	42.7	44.4	29.4	41.0	38.3	42.2
1806	39.0	29.6	32.7	27.7	26.4	25.6	30.0	26.3	24.0	27.0	25.0	24.0	28.1
1807	12.0	12.2	9.6	23.8	10.0	12.0	12.7	12.0	5.7	8.0	2.6	0.0	10.1
1808	0.0	4.5	0.0	12.3	13.5	13.5	6.7	8.0	11.7	4.7	10.5	12.3	8.1
1809	7.2	9.2	0.9	2 5	2.0	7.7	0.3	0.2	0.4	0.0	0.0	0.0	2.5
1810	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1811	0.0	0.0	0.0	0.0	0.0	0.0	6.6	0.0	2.4	6.1	0 8	1.1	1.4
1812	11.3	1.9	0.7	0.0	1.0	1.3	0.5	15.6	5.2	3.9	7.9	10.1	5.0
1813	0.0	10.3	1.9	16.6	5.5	11.2	18.3	8.4	15.3	27.8	16 7	14.3	12.2
1814	22.2	12 0	5.7	23.8	5 8	14.9	18.5	2.3	8.1	19.3	14.5	20.1	13 9
1815	19.2	32.2	26.2	31.6	9.8	55.9	35.5	47.2	31.5	33.5	37.2	65.0	35.4
1816	26.3	68.8	73.7	58.8	44.3	43.6	38.8	23.2	47.8	56.4	38.1	29.9	45.8
1817	36.4	57.9	96.2	26.4	21.2	40.0	50.0	45.0	36.7	25.6	28 9	28.4	41.1
1818	34.9	22 4	29.7	34.5	53.1	36.4	28.0	31.5	26.1	31.7	10.9	25.8	30.4
1819	32.5	20.7	3.7	20.2	19.6	35.0	31.4	26.1	14 9	27.5	25.1	30.6	23.9
1820	19.2	26.6	4.5	19.4	29.3	10.8	20.6	25.9	5.2	9.0	7.9	9.7	15.7

RELATIVE SUNSPOT NUMBERS—(*Continued*)

Date	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1821	21.5	4.3	5.7	9.2	1.7	1.8	2.5	4.8	4.4	18.8	4.4	0.0	6.6
1822	0.0	0.9	16.1	13.5	1.5	5.6	7.9	2.1	0.0	0.4	0.0	0.0	4.0
1823	0.0	0.0	0.6	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	20.4	1.8
1824	21.6	10.8	0.0	19.4	2.8	0.0	0.0	1.4	20.5	25.2	0.0	0.8	8.5
1825	5.0	15.5	22.4	3.8	15.4	15.4	30.9	25.4	15.7	15.6	11.7	22.0	16.6
1826	17.7	18.2	36.7	24.0	32.4	37.1	52.5	39.6	18.9	50.6	39.5	68.1	36.3
1827	34.6	47.4	57.8	46.0	56.3	56.7	42.9	53.7	49.6	57.2	48.2	46.1	49.7
1828	52.8	64.4	65.0	61.1	89.1	98.0	54.3	76.4	50.4	34.7	57.0	46.9	62.5
1829	43.0	49.4	72.3	95.0	67.5	73.9	90.8	78.3	52.8	57.2	67.6	56.5	67.0
1830	52.2	72.1	84.6	107.1	66.3	65.1	43.9	50.7	62.1	84.4	81.2	82.1	71.0
1831	47.5	50.1	93.4	54.6	38.1	33.4	45.2	54.9	37.9	46.2	43.5	28.9	47.8
1832	30.9	55.5	55.1	26.9	41.3	26.7	13.9	8.9	8.2	21.1	14.3	27.5	27.5
1833	11.3	14.9	11.8	2.8	12.9	1.0	7.0	5.7	11.6	7.5	5.9	9.9	8.5
1834	4.9	18.1	3.9	1.4	8.8	7.8	8.7	4.0	11.5	24.8	30.5	34.5	13.2
1835	7.5	24.5	19.7	61.5	43.6	33.2	59.8	59.0	100.8	95.2	100.0	77.5	56.9
1836	88.6	107.6	98.1	142.9	111.4	124.7	116.7	107.8	95.1	137.4	120.9	206.2	121.5
1837	188.0	175.6	134.6	138.2	111.3	158.0	162.8	134.0	96.3	123.7	107.0	129.8	138.3
1838	144.9	84.8	140.8	126.6	137.6	94.5	108.2	78.8	73.6	90.8	77.4	79.8	103.2
1839	107.6	102.5	77.7	61.8	53.8	54.6	84.7	131.2	132.7	90.8	68.8	63.6	85.8
1840	81.2	87.7	55.5	65.9	69.2	48.5	60.7	57.8	74.0	49.8	54.3	53.7	63.2
1841	24.0	29.9	29.7	42.6	67.4	55.7	30.8	39.3	35.1	28.5	19.8	38.8	36.8
1842	20.4	22.1	21.7	26.9	24.9	20.5	12.6	26.5	18.5	38.1	40.5	17.6	24.2
1843	13.3	3.5	8.3	8.8	21.1	10.5	9.5	11.8	4.2	5.3	19.1	12.7	10.7
1844	9.4	14.7	13.6	20.8	12.0	3.7	21.2	23.9	6.9	21.5	10.7	21.6	15.0
1845	25.7	43.6	43.3	56.9	47.8	31.1	30.6	32.3	29.6	40.7	39.4	59.7	40.1
1846	38.7	51.0	63.9	69.2	59.9	65.1	46.5	54.8	107.1	55.9	60.4	65.5	61.5
1847	62.6	44.9	85.7	44.7	75.4	85.3	52.2	140.6	161.2	180.4	138.9	109.6	98.5
1848	159.1	111.8	108.9	107.1	102.2	123.8	139.2	132.5	100.3	132.4	114.6	159.9	124.3
1849	156.7	131.7	96.5	102.5	80.6	81.2	78.0	61.3	93.7	71.5	99.7	97.0	95.9
1850	78.0	89.4	82.6	44.1	61.6	70.0	39.1	61.6	86.2	71.0	54.8	60.0	66.5
1851	75.5	105.4	64.6	56.5	62.6	63.2	36.1	57.4	67.9	62.5	50.9	71.4	64.5
1852	68.4	67.5	61.2	65.4	54.9	46.9	42.0	39.7	37.5	67.3	54.3	45.4	54.2
1853	41.1	42.9	37.7	47.6	34.7	40.0	45.9	50.4	33.5	42.3	28.8	23.4	39.0
1854	15.4	20.0	20.7	26.4	24.0	21.1	18.7	15.8	22.4	12.7	28.2	21.4	20.6
1855	12.3	11.4	17.4	4.4	9.1	5.3	0.4	3.1	0.0	9.7	4.2	3.1	6.7
1856	0.5	4.9	0.4	6.5	0.0	5.0	4.6	5.9	4.4	4.5	7.7	7.2	4.3
1857	13.7	7.4	5.2	11.1	29.2	16.0	22.2	16.9	42.4	40.6	31.4	37.2	22.8
1858	39.0	34.9	57.5	38.3	41.4	44.5	56.7	55.3	80.1	91.2	51.9	66.9	54.8
1859	83.7	87.6	90.3	85.7	91.0	87.1	95.2	106.8	105.8	114.6	97.2	81.0	93.8
1860	81.5	88.0	98.9	71.4	107.1	108.6	116.7	100.3	92.2	90.1	97.9	95.6	95.7

RELATIVE SUNSPOT NUMBERS—(*Continued*)

Date	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1861	62.3	77.8	101.0	98.5	56.8	87.8	78.0	82.5	79.9	67.2	53.7	80.5	77.2
1862	63.1	64.5	43.6	53.7	64.4	84.0	73.4	62.5	66.6	42.0	50.6	40.9	59.1
1863	48.3	56.7	66.4	40.6	53.8	40.8	32.7	48.1	22 0	39.9	37.7	41.2	44.0
1864	57.7	47.1	66.3	35.8	40.6	57.8	54.7	54.8	28.5	33.9	57.6	28.6	47.0
1865	48.7	39.3	39.5	29.4	34.5	33.6	26.8	37.8	21.6	17.1	24.6	12.8	30.5
1866	31.6	38.4	24.6	17.6	12.9	16.5	9.3	12.7	7.3	14.1	9.0	1.5	16.3
1867	0.0	0.7	9.2	5.1	2.9	1.5	5.0	4.9	9.8	13.5	9.3	25.2	7.3
1868	15.6	15.8	26.5	36.6	26.7	31.1	28.6	34.4	43.8	61.7	59.1	67.6	37.3
1869	60.9	59.3	52.7	41.0	104.0	108.4	59.2	79.6	80.6	59 4	77.4	104.3	73.9
1870	77.3	114.9	159.4	160.0	176.0	135.6	132.4	153.8	136.0	146.4	147.5	130.0	139.1
1871	88.3	125.3	143.2	162.4	145.5	91.7	103.0	110.0	80.3	89.0	105.4	90.3	111.2
1872	79.5	120.1	88 4	102.1	107.6	109.9	105.5	92.9	114.6	103.5	112.0	83.9	101.7
1873	86.7	107.0	98.3	76.2	47.9	44.8	66.9	68.2	47.5	47.4	55.4	49.2	66.3
1874	60.8	64.2	46.4	32.0	44.6	38.2	67.8	61.3	28.0	34.3	28.9	29.3	44.7
1875	14.6	22.2	33.8	29.1	11.5	23.9	12.5	14.6	2.4	12.7	17.7	9.9	17.1
1876	14.3	15.0	31.2	2.3	5.1	1.6	15.2	8.8	9.9	14.3	9.9	8.2	11.3
1877	24.4	8.7	11.7	15.8	21.2	13.4	5.9	6.3	16.4	6.7	14.5	2.3	12.3
1878	3.3	6.0	7.8	0.1	5.8	6.4	0.1	0.0	5.3	1.1	4.1	0.5	3.4
1879	0.8	0.6	0.0	6.2	2.4	4.8	7.5	10.7	6.1	12.3	12.9	7.2	6.0
1880	24.0	27.5	19.5	19.3	23.5	34.1	21.9	48.1	66.0	43.0	30.7	29.6	32.3
1881	36.4	53.2	51.5	51.7	43.5	60.5	76.9	58.0	53.2	64.0	54.8	47.3	54.3
1882	45.0	69.3	67.5	95.8	64.1	45.2	45.4	40.4	57.7	59.2	84.4	41.8	59.7
1883	60.6	46.9	42.8	82.1	32.1	76.5	80.6	46.0	52.6	83.8	84.5	75.9	63.7
1884	91.5	86.9	86.8	76.1	66.5	51.2	53.1	55.8	61.9	47.8	36.6	47.2	63.5
1885	42.8	71.8	49.8	55.0	73.0	83.7	66.5	50.0	39.6	38.7	33.3	21.7	52.2
1886	29.9	25.9	57.3	43.7	30.7	27.1	30.3	16.9	21.4	8.6	0.3	12.4	25.4
1887	10.3	13.2	4.2	6.9	20.0	15.7	23.3	21.4	7.4	6.6	6.9	20.7	13.1
1888	12.7	7.1	7.8	5.1	7.0	7.1	3.1	2.8	8.8	2.1	10.7	6.7	6.8
1889	0.8	8.5	7.0	4.3	2.4	6.4	9.7	20.6	6.5	2.1	0.2	6.7	6.3
1890	5.3	0.6	5.1	1.6	4.8	1.3	11.6	8.5	17.2	11.2	9.6	7.8	7.1
1891	13.5	22.2	10.4	20.5	41.1	48.3	58.8	33.2	53.8	51.5	41.9	32.2	35.6
1892	69.1	75.6	49.9	69.6	79.6	76.3	76.8	101.4	62.8	70.5	65.4	78 6	73.0
1893	75.0	73.0	65.7	88.1	84.7	88.2	88.8	129.2	77.9	79.7	75.1	93.8	84.9
1894	83.2	84.6	52.3	81.6	101.2	98.9	106.0	70.3	65.9	75.5	56.6	60.0	78.0
1895	63.3	67.2	61.0	76.9	67.5	71.5	47.8	68.9	57.7	67.9	47.2	70.7	64.0
1896	29.0	57.4	52.0	43.8	27.7	49.0	45.0	27.2	61.3	28.4	38.0	42.6	41.8
1897	40.6	29.4	29.1	31.0	20.0	11.3	27.6	21.8	48.1	14.3	8.4	33.3	26.2
1898	30.2	36.4	38.3	14.5	25.8	22.3	9.0	31.4	34.8	34.4	30.9	12.6	26.7
1899	19.5	9.2	18.1	14.2	7.7	20.5	13.5	2.9	8.4	13.0	7.8	10.5	12.1
1900	9.4	13.6	8.6	16.0	15.2	12.1	8.3	4.3	8.3	12.9	4.5	0.3	9.5

RELATIVE SUNSPOT NUMBERS—(*Continued*)

Date	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1901	0.2	2.4	4.5	0.0	10.2	5.8	0.7	1.0	0.6	3.7	3.8	0.0	2.7
1902	5.2	0.0	12.4	0.0	2.8	1.4	0.9	2.3	7.6	16.3	10.3	1.1	5.0
1903	8.3	17.0	13.5	26 1	14.6	16.3	27.9	28.8	11.1	38.9	44.5	45.6	24.4
1904	31.6	24.5	37.2	43.0	39.5	41.9	50.6	58.2	30.1	54.2	38 0	54.6	42.0
1905	54.8	85.8	56.5	39.3	48.0	49 0	73.0	58.8	55.0	78.7	107.2	55.5	63.5
1906	45.5	31.3	64.5	55.3	57.7	63.2	103.3	47.7	56.1	17.8	38 9	64.7	53.8
1907	76.4	108.2	60.7	52.6	43.0	40.4	49.7	54.3	85.0	65.4	61.5	47.3	62.0
1908	39.2	33.9	28.7	57.6	40.8	48.1	39.5	90.5	86.9	32.3	45.5	39.5	48.5
1909	56.7	46.6	66.3	32.3	36.0	22.6	35.8	23.1	38.8	58.4	55 8	54.2	43.9
1910	26.4	31.5	21.4	8.4	22.2	12.3	14.1	11.5	26.2	38.3	4.9	5.8	18.6
1911	3.4	9.0	7.8	16.5	9.0	2.2	3.5	4.0	4.0	2.6	4.2	2.2	5.7
1912	0.3	0.0	4.9	4.5	4.4	4.1	3.0	0.3	9.5	4.6	1.1	6.4	3.6
1913	2.3	2.9	0.5	0.9	0.0	0.0	1.7	0.2	1.2	3.1	0.7	3.8	1.4
1914	2.5	2.6	3.1	17.3	5.3	11.4	5.4	7.8	12.8	8.1	16.1	22.2	9.6
1915	23.0	42.3	38.8	41.3	33.0	68.8	71.6	69.6	49.5	53.5	42.5	34.5	47.4
1916	45.3	55.4	67.0	71.8	74.5	67.7	53.5	35.2	45.1	50.7	65.6	53.0	57.1
1917	74.7	71.9	94.8	74.7	114.1	114 9	119.8	154.5	129 4	72.2	96.4	129.3	103.9
1918	96.0	65.3	72.2	80.5	76.7	59.4	107.6	101.7	79.9	85.0	83.4	59.2	80.6
1919	48.1	79.5	66.5	51.8	88.1	111.2	64.7	69.0	54.7	52.8	42.0	34.9	63.6
1920	57.3	50.9	71.9	14.3	33.7	38.8	26.5	18.6	38.7	48.8	24.6	39.9	38.7
1921	28.8	27.6	27.5	30.5	22.3	34.5	42.4	20.8	16.7	16.1	13.4	15.7	24.7
1922	10.2	27.9	60.0	11.4	7.7	5.8	9.7	5.3	5.2	8.1	6.7	18.7	14.7
1923	4.5	1.5	3.3	6.1	3.2	9.1	3.5	0.5	13.2	11.6	10.0	2.8	5.8
1924	0.5	5.1	1.8	11.3	20.8	24.0	28.1	19.3	25.1	25.6	22.5	16.5	16.7
1925	5.5	23.2	18.0	31.7	42.8	47.5	38.5	37.9	60.2	69.2	58.6	98.6	44.3
1926	71.8	70.0	62.5	38.5	64.3	73.5	52.3	61.6	60.8	71.5	60.5	79.4	63.9
1927	81.6	93.0	69.6	93.5	79.1	59.1	54.9	53.8	68.4	63.1	67.2	45.2	69.0
1928	83.5	73.5	85.4	80.6	76.9	91.4	98.0	83.8	89.7	61.4	50.3	59.0	77.8
1929	68.9	64.1	50.2	52.8	58.2	71.9	70.2	65.8	34.4	54.0	81.1	108.0	65.0
1930	65.3	49.2	35.0	38.2	36.9	28.8	21.9	24.9	32.1	34.4	35.6	25.8	35.7
1931	14.6	43.1	30.0	31.2	24.6	15.3	17.4	13.0	19.0	10.0	18.7	17.8	21.2
1932	12.1	10.6	11.2	11.2	17.9	22.2	9.6	6.8	4.0	8.9	8.2	11.0	11.1
1933	12.3	22.2	10.1	2.9	3.2	5.2	2 8	0.2	5.1	3.0	0.6	0.3	5.7
1934	3.4	7.8	4.3	11.3	19.7	6.7	9 3	8.3	4.0	5.7	8.7	15.4	8.7
1935	18.9	20.5	23.1	12.2	27.3	45.7	33.9	30.1	42.1	53.2	64.2	61.5	36.1
1936	60.4	73.8	77.7	77.1	54.1	70.5	52.4	67.6	75.1	85.5	113.4	117.5	79.7
1937	132.5	128.5	83.9	109.3	116.7	130.3	145.1	137.7	100.7	124.9	74.4	88.8	114.4
1938	98 4	119.2	86.5	101.0	127.4	97.5	165.3	115.7	89.6	99.1	122.2	92.7	109.6
1939	80.3	77.4	64.6	109.1	118.3	101.0	97.6	105.8	112.6	88.1	68.1	42.1	88.8
1940	50.5	59.4	83.3	60.7	54.4	83.9	67.5	105.5	66.5	55.0	58.4	68.3	67.8

RELATIVE SUNSPOT NUMBERS—(*Continued*)

Date	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1941	45.6	44.5	46.4	32.8	29.5	59.8	66.9	60.0	65.9	46.3	38.3	33.7	47.5
1942	35.6	52.8	54.2	60.7	25.0	11.4	17.7	20.2	17.2	19.2	30.7	22.5	30.6
1943	12.4	28.9	27.4	26.1	14.1	7.6	13.2	19.4	10.0	7.8	10.2	18.8	16.3
1944	3.7	0.5	11.0	0.3	2.5	5.0	5.0	16.7	14.3	16.9	10.8	28.4	9.6
1945	18.5	12.7	21.5	32.0	30.6	36.2	42.6	25.9	34.9	68.8	46.0	27.4	5.71
1946	47.6	86.2	76.6	75.7	84.9	73.5	116.2	107.2	94.4	102.3	123.8	121.7	92.5
1947*	116.0	132.3	129.8	149.9	206.5	106.9	168.6	196.1	175.5	181.6	127.4	116.6	150.1

*Provisional numbers for 1947.

NAME INDEX

SUBJECT INDEX